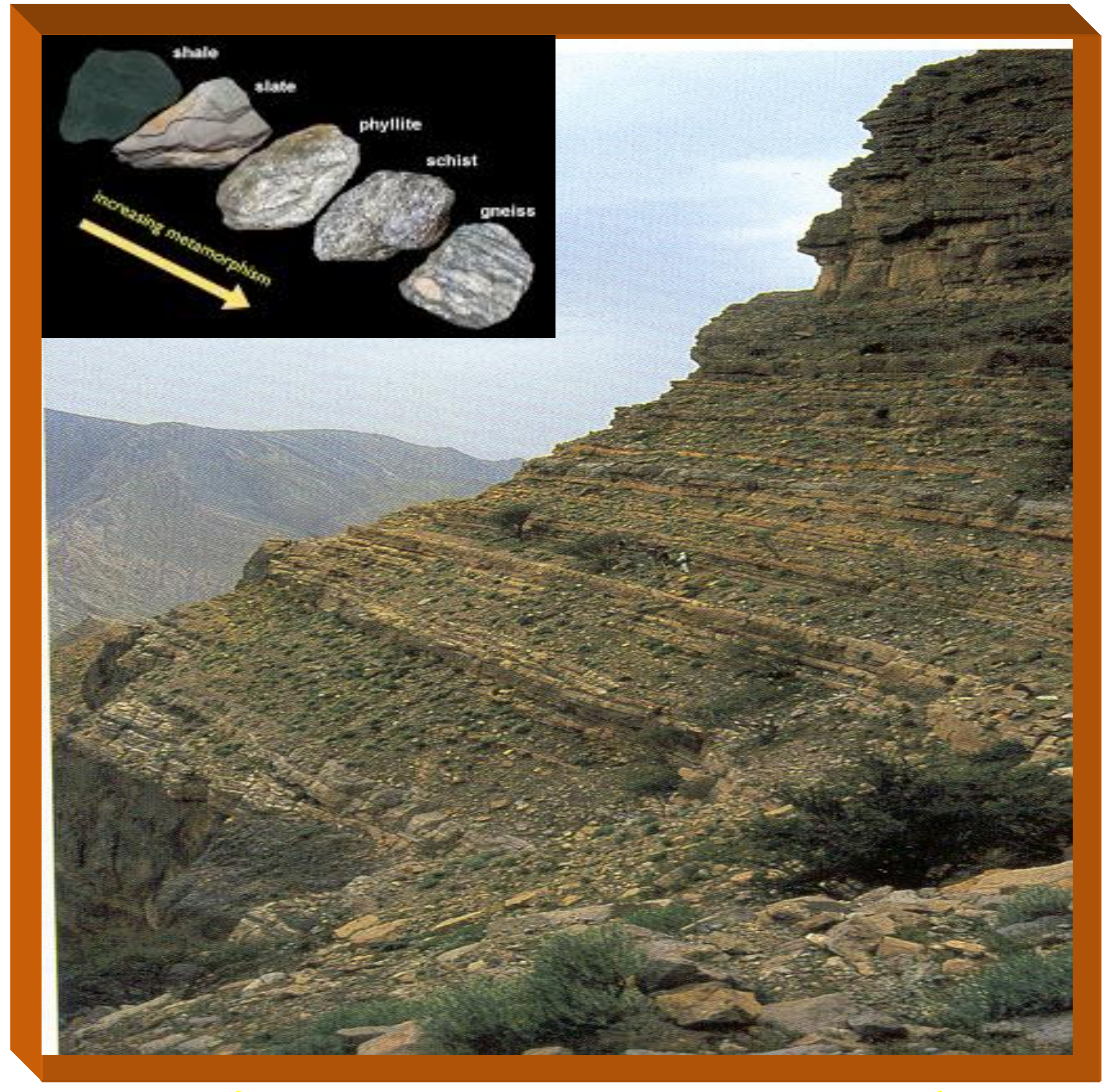
Metamorphic Rocks



Dr. Emad Khalil

Faculty of Science - Zagazig University



رقم الإيداع : 11429
الترقيم الدولي : 3- 3202 -90 -977 -978

الإهــــــداء

إليك ربي اهـدي عملي هـذا عله يكـون سجـلاً ولو صغيـراً في صحيفة أعمالي

اللهـم بـارك لـي وبـارك فـي وارض عنـي

فـأن رضـاك هو جـل مبتغـاي

والحمـد اللـه رب العالميـن

* * * * * * * * * * * *

Contents

CHAPTER 1: Definition And Types Of Metamorphism.

CHAPTER 2: Metamorphic grades And Depth zones and metamorphism .

CHAPTER 3: Classification of metamorphic rocks.

CHAPTER 4: Types of Metamorphic Reactions.

CHAPTER 5: Metamorphic Rock Textures.

CHAPTER 6: Metamorphic Facies .

CHAPTER 7: Common Types of metamorphic rocks.

CHAPTER 8: Minerals in Metamorphic rocks.

CHAPTER 9: Metamorphism of Pelitic Sediments.

CHAPTER 10: Metamorphism of Calcareous rocks.

CHAPTER 11: Metamorphism of Sandstone.

CHAPTER 12: Metamorphism of Spilitic basalt .

CHAPTER 13: Metamorphism and Tectonics.

REFERENCES :

INTRODUCTION

Metamorphism - what is It ?

Metamorphism means to change form. In the geologist's sense it refers to changes in rocks (protoliths) in the solid state (i.e. not by melting the rock wholesale). One can view metamorphism as similar to cooking. Ingredients are mixed and placed at a different temperature (and/or pressure) and changes occur.

Change occurs in order to maintain equilibrium conditions with new states of heat, pressure, or fluids. Thus, major changes in any of these three environmental variables can result in metamorphism. Because of the great conveyor belt of plate tectonics, rocks can encounter a variety of environmental conditions riding around in pressure, temperature, fluid space. As they go, they may metamorphose and may have a tale to tell of where they've been.

Metamorphic rocks are derived from materials of igneous, sedimentary or metamorphic rocks by changing their physical form and /or mineralogical composition as a result of changes in pressure and /or temperature or by the effect of a fluid phase. Metamorphism occurs in the solid state and is bounded by sedimentary diagenesis and igneous melting. Metamorphic changes are always in a direction which tends to restore equilibrium. The effects of metasmorphism include:

1- Chemical recombination and growth of new minerals with or without the addition of new elements from circulating fluids.
2 - Deformation and rotation of the constituent mineral grains .
3-Recrystallization of minerals into larger grains.

<u>Factors of Metamorphism</u>:

1- Temperature (T)
2-Pressure (P)
3- Fluids

<u>Grades of Metamorphism</u>:

Winkler (1967) divided the entire P,T ranges of metamorphic conditions into four large large divisions of metamorphic grade. The boundaries between the four grades is marked by significant changes of mineral assemblages (specific mineral reactions):
1- Verly low-grade: diagnostic minerals are laumonite, prhenite, pumpellite, lawsonite, illite with imperfect crystallinity.
2- Low-grade: characteristic mineral assemblage is : chlorite+zoisite/clinozoisite, actinolite, quartz, chloritoid.
3- Medium-grade: appearance of cordierite, or staurolite
4- Hig grade:: breakdown of muscovite in the presence of quartz and plagioclase, formation of migmatites.

Preesure divisions:
1-Very-low grade: laumontite ----lawsonite----glaucophane---jadiete+quartz
2-Low-grade: almandine---glaucophane+clinozoisite
3-Medium-grade: cordierite----almandine + (Al2SiO5-polymorph)
4- High-grade:cordierite----cordierite-almandine----almandine

Metamorphic Zones (Barrows Zones):
change in bulk composition of the rock (Metasomatism).
In most regions of metamorphic rocks, a variation of grain size and mineralogy occurs which suggests a variation in metamorphic grade. The grain size of the rocks tends to become coarser with increasing temperature. Barrow (1912) was the first to recognize that certain newly formed minerals appear in a definite sequence with increasing temperature. These minerals were designated as index minerals. The metamorphic zones characterized by these index minerals are well developed on a regional scale in most continents.. The following succession of index minerals with increasing temperature can be distinguished in many terrains:
1-Chlorite zone: chlorite-muscovite phyllite or schist
2-Biotite zone: appearance of biotite (biotite isograde)
3-Almandine (garnet) zone: appearance of garnet.
4- Staurolite zone: appearance of staurolite
5-Kyanite zone: appearance of kyanite
6-Sillimanite zone: appearance of sillimanite and disappearance of kyanite.
An isograde is a line of outcrops on which a mineral assemblage begins to appear or disappear. Isogrades give a general picture of the P-T distribution in a metamorphic terrane.
Mineral assemblage (paragensis) : A number of different minerals in contact within a single thin section.

Classification of Metamorphic Rocks :
This Chapter is discussed in details by :
A- **Textural Classification:**
Two major groups of metamorphic rocks are recognized:
1- Those which are foliated (posses a definit planar structure)
2- Those which are not foliated but are massive and structureless.
The foliated rocks may be further subdivided according to the type of foliation. A large varity of types may be subsequently be recognized in each group according to the dominant minerals.
B- **Chemical and Mineralogical Classification**
1-Pelitic: Derivitives of pelitic (aluminous) sediments. Abundance of micas is characteristic.
2- Quartzfeldspathic: The principal minerals are quartz and feldspar (e.g., metamorphosed sandstones, siliceous tuffs, granites)
3- Calcareous: Derivatives of limestones , marls and dolomites.. Typicall calcite is abundant. Also characteristic are calcium and magnesium silicate such as diopside, tremolite, wollastonite and grossularite.
4- Basic : Derivative of basic igneous rocks (basalt, gabbro… et c.). Characteristic minerals are plagioclase, hornblende, Mg-chlorite, epidote.
5- Ultra-basic: Deriviativ e of peridotites. Abundance of Mg-minerals (antigorite, talc, anthophyllite, magneiste, brucite, Mg-chlorites) and absence of feldspar are characteristic.

6-Ferrugineous and manganiferous: Derviatives of cherts and other sediments containing abundant iron and /or manganese. Quartz is abundant, but feldspar is absent in typical metacherts. Magnetite, hmeatite, spessartite-almandite garnet, ferrohypersthene, stilpnomelane, Mn-epidotes and pyroxenoids are found in various combination.

Categories of Metamorphism:

Metamorphic rocks are divided on the basis of their field occurrence into the following categories:

1- Contact (Thermal) Metamorphism:

It is the recrystallization of rocks near the contacts of igneous intrusions due to rise in temperature. The area surrounding an intusive body is called contact aurole.

2 - Regional (Orogenic) Metamorphism :

This type outcrops over large areas and in a variety of settings. Rocks subjected to regional metamorphism occur in a great belt, hundreds or thousands of kilometers long and wide.

Metamorphism produced as a result of the progressive increase in temperature and pressure, i.e. by burial of a rock within the earth, is termed prograde metamorphism and in general terms is characterized by dehydration reactions, which release water. With increasing depth of burial the pressure and temperature of the material increases along the follwong gradients:

P gradient 3.5 kbar/10 km •T gradient 20-30°C/km

3 - Pyrometamorphism:

It is recrystallization at high temperatures and takes place in felsic, mafic and ultramfic xenoliths included in volcanic rokcs. It is an extraordinary kinds of thermal metamorphism. It may produce partila melting. Buchite is a partially melted rock derived from shael or sandstone.

4-Ocean-Floor Metamorphism:

It is the recrystallzation of of deeper part of the basic and ultrabasic rocks of the oceanic crust, mainly beneath the crest of the mid-ocean ridges.

5-Hydrothermal Metamoprhism :

It is the recrystallization of rokcs under the influence of a hot fluid phase introduced from the outside, mainly in geothermal fields.

6-Cataclastic (dynamic, dislocation) Metamorphism :

It is the crushing and grinding of rocks as a result of fault movement

7 - Impact Metamorphism :

This type occurs near the impact size of large meteorites.

Textures and structures of metamorphic rocks :

The orientation and arrangement of minerals in metamorphic rocks differ in different rocks, though the regional metamorphic rocks have textural similarities, as do the contact metamoprhic rocks. At the same time, a single rock may contain several textures or textural elements. The most important textures are as follows:

Foliation :

(Give your remarks on each texture in lab. How it looks like?) It is a planar element in metamoprhic rocks. It is defined as the parallel arrangement or distribution of minerals which ncludes layring of different mineralogical composition as in a gneiss and parallel arrangement of platy minerals (schistosity) as in a schist, closed spaced

fracture (slaty clevage). It is usually developed during metamorphism by direct pressure which cause differential movement or recrystallization.

Schistosity:

The parallel arrangment of tabular minerals (Mica, amphiboles…etc.) to give a more or less planar fissility. With decrease in grain size, this grades to slaty cleavage (slate). Stretched or flattened grains, such as in quartz in deformed quartzites, may also form schistosity.

Gneissosity:

The alternation of lighter and darker layers, such as micaceous or amhibole-ric layers with quartzfeldspathic layers. The term is often used to include metamorphic layering regardless of its origin.

Lineation :

The parallel alignment of linear elements in the rock. It includes aligned prismatic grains, aggregates of grains, axes of microfolds, and lines of intersection of two or more schistosities.

Prefered Orientation:

This denote parallelism of tabular or elongated grains, as in schistosity or lineation-equidimensional grains according to their crystal lattice orientations (e.g. c-axes in quartz).

Hornfelsic and Granoblastic :

This is a non-directional texture. Planar or prismatic grains if present, are not oriented. The term granoblastic is used for coarse-grained texture and hornflesic to finer-grained rocks.

Porphyroblastic :

Large crystals of a mineral grown in a solid medium of smaller grains. It is comparable to phenocrysts in igneous rocks.

Poikiloblastic :

It is a porphyroblast containing numerous inclusions of one or more groundmass minerals enveloped during growth (equivalent to sieve texture in igneous rocks)

Helicitic texture :

Direction of an earlier foliation is reflected in curved lines of inclusions that are preserved within a porhphyroblast. Often S-shaped as might be formed by rolling of a porphyroblast during growth.

Corona (reaction rim) :

A new mineral forms as a rim around a mineral that is no longer in its field of stability (e.g., actinolite around augite).

Porphyroclast :

Coarse, strained, and broken crystals in a finer-grianed matrix.

Augen (eye-shaped):

Lage eyes (porphyroclasts) of feldspar in a finer grained gneissic matrix.

Mylonitic Extremely granulated and streaked-out grains-typically foliated and containing ovoid relict crystals.

Catalcalstic:

Sheared and crushed rock fabric, not as extreme as mylonitic. Nature of the original rock is recognizable from the undestroyed fragments.

Flaser:

A cataclastic texture in which undestroyed eyes of the original rock swim in granulated streasks and laminae.

Common Metamorphic Rocks :

Foliated - Contain linear or planar features. Form in response to active pressure during regional metamorphism. Foliation is not to be confused with the original sedimentary layering.

Slate - Fine grained, with nice rock cleavage. Cleavage due to the parallel orientation of the mica grains.

Phyllite - Well developed foliation. Grains slightly larger than those of a slate. Again composed of mica. Poorer rock cleavage.

Schist - Contains grains that can be seen by the eye. Still has noticeable foliation. May be most common of all metamorphic rocks.

Gneiss - Consists of alternating light (feldspar-quartz) and dark (amphibole-biotite) bands. Requires a higher degree of metamorphism.

Non-foliated - Show no evidence of foliation and are apt to form in a contact metamorphic environment where pressure is unimportant.

Marble - Recrystallized limestone (calcite).

Quartzite - Metamorphosed quartz sandstone.

Hornfels - "Spotted rock" due to the presence of large crystals in a fine-grained matrix.

Metamorphic facies:

An assemblage of minerals that reached equilibrium under a specific set of temperature and pressure conditions. Each facies named for a readily recognizable characteristic mineral or other feature. Remember that any one mineral does not have to be present, the facies is characterized by several different minerals:

1. Zeolite - Transitional from sedimentary conditions. P 2-4 kb and T 200-300 degrees C.
2. Greenschist - Low temperature and pressure facies of regional metamorphism. P 3-8 kb and T 300-500 degrees C. Characterized by the green minerals chlorite, epidote and actinolite.
3. Amphibolite - Moderate to high temperature and low pressure regional metamorphic facies. P 3-8 kb and T 500-700 degrees C. Characterized by the presence of amphibole.
4. Granulite - High temperature and low to moderate pressure regional metamorphic facies. P 3-12 kb and T >650 degrees C. Characterized by quartz, feldspar, same minerals in a granite, hence the name.
5. Blueschist - Low temperature and high pressure metamorphic facies. Occurs only in areas of abnormally low geothermal gradients. P >4 kb and T 200-450 degrees C. Name from the blue mineral glaucophane. Common rock type on Catalina Island. Actually very rare in much of the world.

6- Eclogite - Mantle rock, probably not a valid metamorphic facies. Requiresk- P >10 kb and T from 350-750 degrees C.

Plate tectonic settings of metamorphism:

Hydrothermal metamorphism occurs near mid-ocean ridges driven by the heat of the volcanic activity there. Intrusion of igneous rocks drives contact metamorphism anywhere it occurs. Both of these sorts are metamorphism with high temperatures and low pressures. Faults associated with plate boundaries create cataclastic metamorphismin the shallow crust. Cataclasis grades into totally pulverized minerals that are streaked out in bands characteristic of mylonites.

CHAPTER 1

Definition ، Agents of Metamorphism And Types of Metamorphism

The word "***Metamorphism***" comes from the Greek: Meta = change, Morph = form, so metamorphism means to change form. In geology this refers to the changes in mineral assemblage and texture that result from subjecting a rock to pressures and temperatures different from those under which the rock originally formed.

The original rock that has undergone metamorphism is called the ***protolith***. Protolith can be any type of rock and sometimes the changes in texture and mineralogy are so dramatic that is difficult to distinguish what the protolith was.

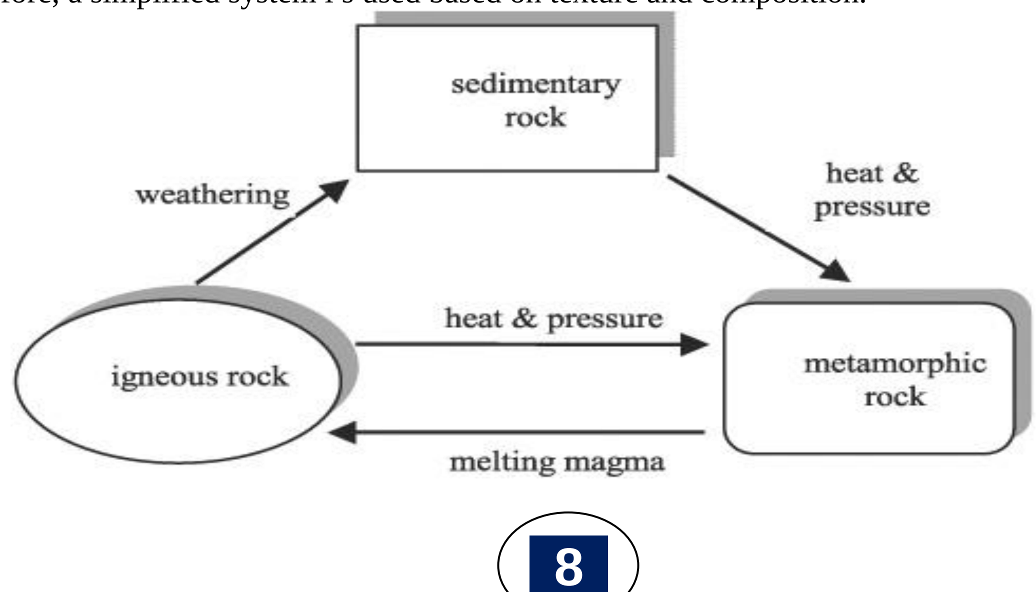
Types of Protolith:

1.Pelitic/mudrocks - high Al, K, Si.
2. Quartzo-feldspathic - high Si, Na, K, Al.
3. Calcareous- high Ca, Mg, CO_2.
4. Mafic- high Ca, Mg, Fe .
5. Ultramafic- very high Mg, Fe, low Si, Al.

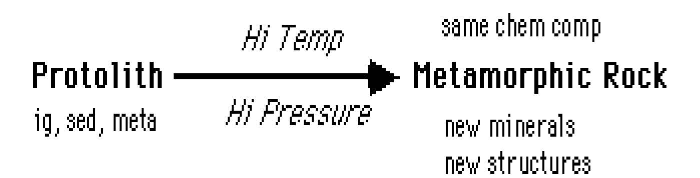
During metamorphism the protolith undergoes changes in texture of the rock and the mineral make up of the rock. These changes take place mostly in the solid state and are caused by changes in physical or chemical conditions, which in turn can be caused by such things as burial, tectonic stress, heating by magma or interactions with fluids.

Metamorphic Rocks:

Metamorphic rocks are rocks that have undergone a change from their original form due to changes in temperature, pressure or chemical alteration. The classification of metamorphic rocks is based on the minerals that are present and the temperature and pressure at which these minerals form. Determination of this information is not easily accomplished in this lab. Therefore, a simplified system i s used based on texture and composition.



When rocks are subjected to elevated temperatures and pressures, for example due to deep burial in **orogenic** (mountain building) zones when two continents collide, they may become **metamorphosed** (metamorphism is from the Greek, to change in form). They slowly recrystallize while remaining in the solid state. This may takes thousands or millions of years. Metamorphism is essentially an **isochemical process**, i.e. the bulk chemical composition of a rock body is more or less unchanged from the **protolith**, or original rock. But the minerals may be largely **recrystallized** into a new mineral assemblage. In addition, new structural features are frequently imparted to the rocks, such as **slaty cleavage** or **schistosity**.



Metamorphism:

Metamorphism is the solid-state recrystallization of pre-existing rocks due to changes in physical and chemical conditions, primarily heat, pressure, and the introduction of chemically active fluids. Mineralogical, chemical and crystallographic changes can occur during this process. Changes at or just beneath Earth's surface due to weathering and/or diagenesis are not classified as metamorphism.

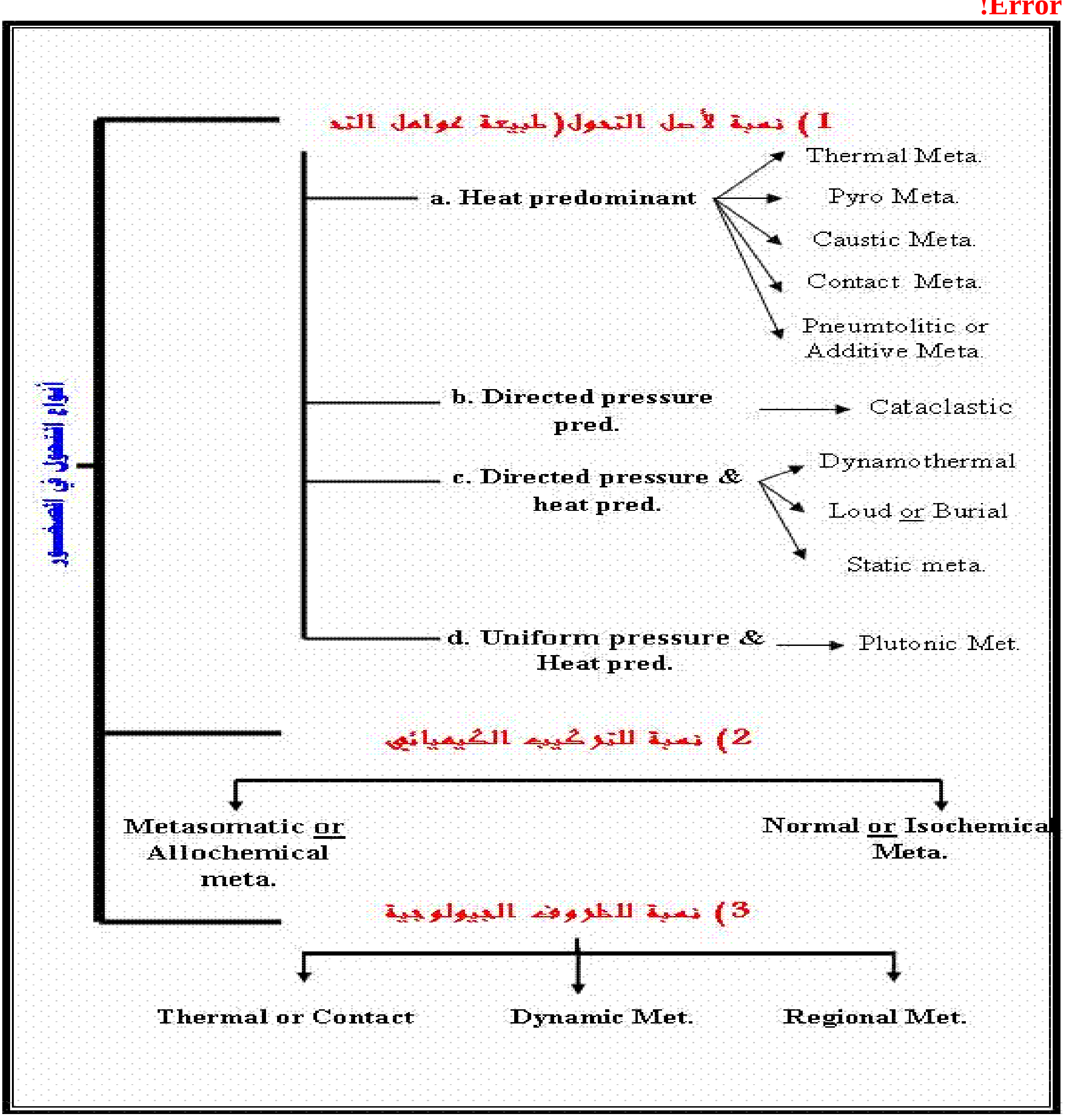
Three types of metamorphism exist: contact, dynamic and regional. Metamorphism produced with increasing pressure and temperature conditions is known as *prograde metamorphism*. Conversely, decreasing temperatures and pressure characterize *retrograde metamorphism*.

Limits of metamorphism:

The temperature lower limit of metamorphism is considered to be 100 - 200 °C, to exclude diagenetic changes, due to compaction, which result in sedimentary rocks. There is no agreement on a pressure lower limit. Some workers argue that changes in atmospheric pressures are not metamorphic, but some types of metamorphism can occur at extremely low pressures.

The upper boundary of metamorphic conditions is related to the onset of melting processes in the rock. The maximum temperature for metamorphism is typically 700 - 900 °C, depending on the pressure and on the composition of the rock. Migmatites are rocks formed at this upper limit, which contain pods and veins of material that has started to melt but has not fully segregated from the refractory residue. Since the 1980s it has been recognized that, rarely, rocks are dry enough and of a refractory enough composition to record without melting "ultra-high" metamorphic temperatures of 900 - 1100 °C.

!Error



أنواع التحول في الصخور
1) نسبة لأصل التحول (طبيعة عوامل التح
a. Heat predominant
Thermal Meta.
Pyro Meta.
Caustic Meta.
Contact Meta.
Pneumtolitic or Additive Meta.
b. Directed pressure pred.
Cataclastic
c. Directed pressure & heat pred.
Dynamothermal
Loud or Burial
Static meta.
d. Uniform pressure & Heat pred.
Plutonic Met.
2) نسبة للتركيب الكيميائي
Metasomatic or Allochemical meta.
Normal or Isochemical Meta.
3) نسبة للظروف الجيولوجية
Thermal or Contact
Dynamic Met.
Regional Met.

Agents of Metamorphism:

The Role of Temperature:

Changes in temperature conditions during metamorphism causes several important processes to occur - first, temperature is a measure of energy. With increasing temperature, and thus higher energy, chemical bonds are able to break and reform. Thus, the breaking and making of crystal bonds drive the chemical reactions that change a rock's chemistry during metamorphism. Secondly, increasing temperature results in the growth of crystals. Within a rock, a small number of large crystals have a higher thermodynamic stability than do a large number of small crystals. As a result, increasing temperature during metamorphism, even in the absence of any chemical change, will generally result in the amalgamation of small crystals to produce a coarser grained rock. Thirdly, individual minerals are only stable over specific temperature ranges. Thus, as temperature changes, minerals within a rock become unstable and transform through chemical reactions to new minerals. This property is very important to our interpretation of metamorphic rocks. By observing the mineral assemblage (set of minerals) within a metamorphic rock, it is often possible to make an estimate of the temperature at the time of formation. That is, minerals can be used as thermometers of the process of metamorphism. Finally, increasing temperature tends to cause chemical reactions to occur at a faster rate such that those reactions that are chemically favorable will occur with greater speed during metamorphism.

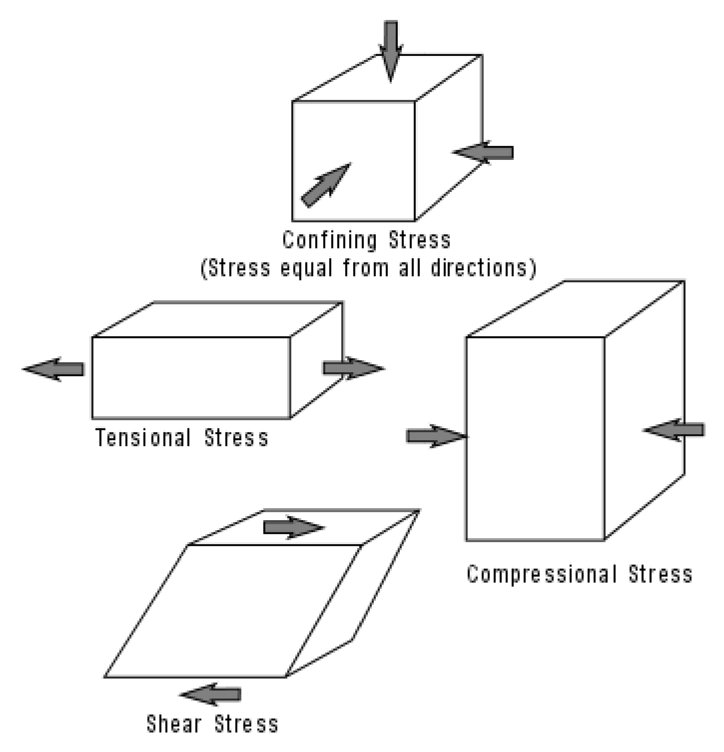
The Role of Pressure:

Pressure, the second of the two physical parameters controlling metamorphism, occurs in two forms. The most widely experienced type of pressure is lithostatic. This "rock-constant" pressure is derived from the weight of overlying rocks. Lithostatic pressure is experienced uniformly by a metamorphic rock. That is, the rock is squeezed to the same degree in all directions. Thus, there is no preferred orientation to lithostatic pressure and there is no mechanical drive to rearrange crystals within a metamorphic rock experiencing lithostatic conditions. Conversely, directed pressure, the second type of pressure associated with metamorphism, is the pressure of motion and action. Plate tectonics provide the underlying mechanical control for all forms of directed pressure. Thus, metamorphism is closely linked to the plate tectonic cycle and many metamorphic rocks are the products of tectonic interactions.

As was the case with changes in temperature, changes in pressure, either lithostatic or directed, have important impacts upon the stability of minerals. Every mineral is stable over a range of pressures, if pressure conditions during metamorphism exceed a mineral's stability range the mineral will transform to a new phase. Many of these solid-state reactions involve polymorphic transformation – changes between minerals with the same chemistry and different crystallographic structures. Just as with temperature, mineral assemblages within a metamorphic rock can be used as a barometer to measure pressure at the time of formation. Additionally, the application of directed pressure to a metamorphic rock results in the alignment of grains. Such alignment will occur when mineral grains are either elongate or platy in form. As we will learn, this alignment is responsible for producing the textures observed in a large group of metamorphic rocks.

• Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress***, or ***uniform stress.***

If the stress is not equal from all directions, then the stress is called a ***differential stress.***

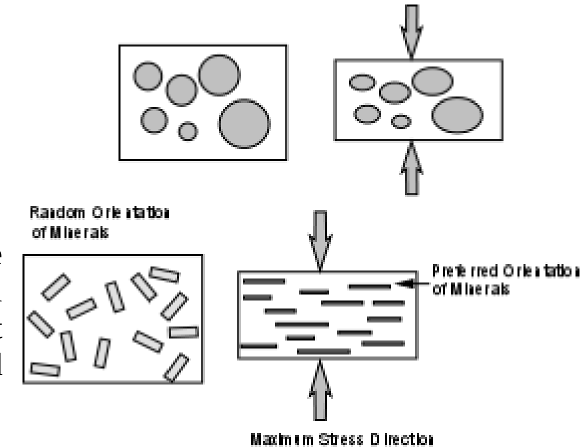


There are two kinds of differential stress. ***Normal stress*** causes objects to be compressed in the direction of maximum principal stress and extended in the direction of minimal stress. If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock. ***Shear stress*** causes objects to be smeared out in the direction of applied stress.

Differential stress if acting on a rocks can have a profound affect on the appearance or texture of the rock.

Rounded grains can become flattened in the direction of maximum stress.

Minerals that crystallize or grow in the differential stress field can have a preferred orientation. This is especially true of the sheet silicate minerals (the micas: biotite and muscovite, chlorite, talc, and serpentine).



These sheet silicates will grow with their sheets orientated perpendicular to the direction of maximum stress. Preferred orientation of sheet silicates causes rocks to be easily broken along approximately parallel sheets. Such a structure is called a ***foliation***.

• Fluid Phase.- Any existing open space between mineral grains in a rock can potentially contain a fluid. This fluid is mostly H_2O, but contains dissolved ions. The fluid phase is important because chemical reactions that involve changing a solid mineral into a new solid mineral can be greatly speeded up by having dissolved ions transported by the fluid. If chemical alteration of the rock takes place as a result of these fluids, the process is called ***metasomatism***.

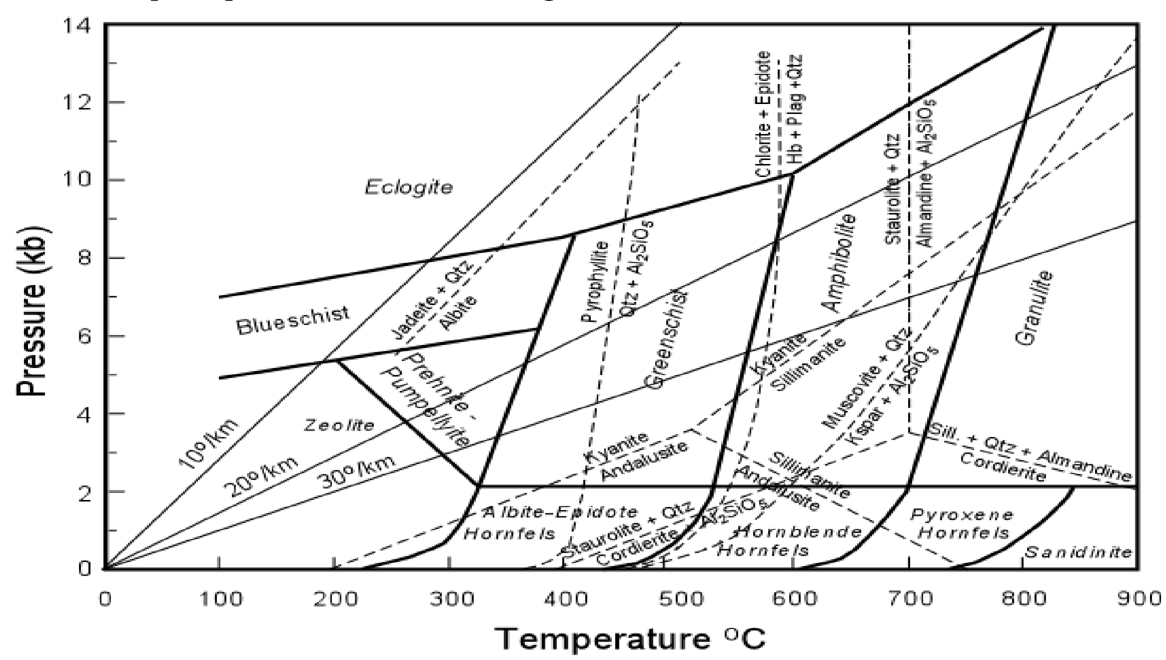
Time - Because metamorphism involves changing the rock while it is solid, metamorphic change is a slow process. During metamorphism, several processes are at work. Recrystallization causes changes in minerals size and shape. Chemical reactions occur between the minerals to form new sets of minerals that are more stable at the pressure and temperature of the environment, and new minerals form as a result of polymorphic phase transformations (recall that polymorphs are compounds with the same chemical formula, but different crystal structures.

Fluids :

Fluid phases of volatile constituents (H2O, CO2, CO, CH4) are usually present during metamorphism. The presence of water greatly increase the rate of crystallization due to the catalytic action of water.

Estimating Pressure and Temperature of Metamorphism:

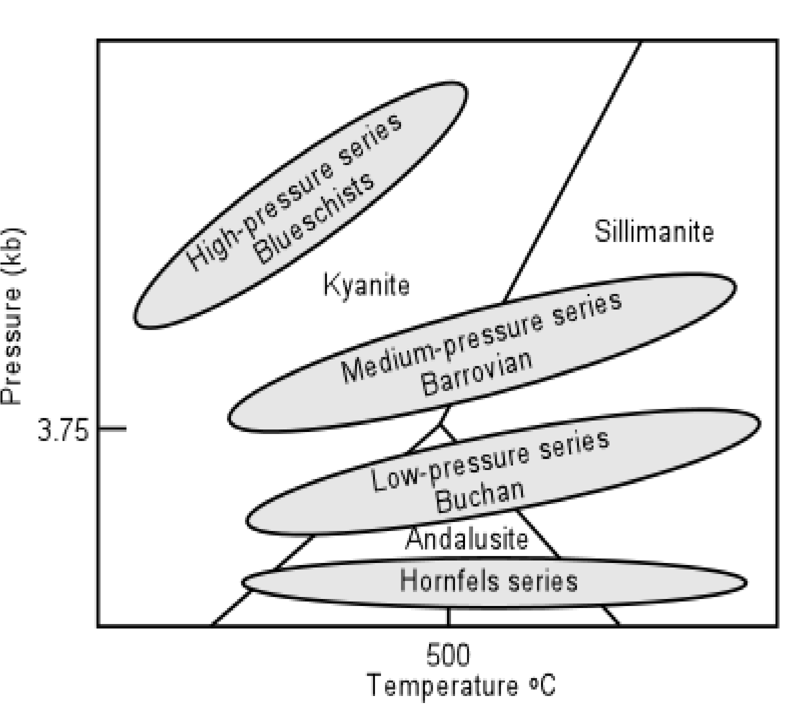
Using combinations of reactions that have likely taken place during metamorphism, petrologists have been able over the years to determine the pressure and temperature of metamorphism in a variety of rocks, and in so doing have been able to place constraints on the fields of temperature and pressure for the various metamorphic facies. Some of these reactions that have been determined experimentally, are shown in the diagram below with reaction boundaries superimposed over the facies diagram.



The diagram also shows various geothermal gradients that would control the succession of facies encountered during prograde metamorphism if the rocks were pushed down into the Earth along one of these geothermal gradients.

- A low geothermal gradient of around 10^o/km would cause prograde metamorphism to occur along a sequence of facies from zeolite to blueschist to eclogite. Such a progression is termed a facies series, and in general terms this would be called a high pressure facies series, as shown in the diagram below. Such a facies series would be expected in areas near subduction zones where cool lithosphere is pushed to higher pressure.

- A geothermal gradient of around 30^o/km, expected in areas undergoing an orogenic event, would produce a succession of facies from zeolite to prehnite pumpellyite to greenschist to amphibolite to granulite. Note that in pelitic rocks of this series, the Al_2SiO_5 minerals would change from kyanite to sillimanite somewhere in the amphibolite facies. This facies series is termed the Medium pressure series or Barrovian facies series.



Note that a slightly higher geothermal gradient would produce the same succession of facies, but pelitic rocks would show a change in the Al_2SiO_5 minerals from kyanite to andalusite to sillimanite. This facies series is called the Low-pressure series or Buchan facies series.

- Along very high geothermal gradients, such as might be expected in the vicinity of intruding magmas the succession of facies would increase from the albite-epidote hornfels facies to the hornblende hornfels facies to pyroxene hornfels and sanidinite facies, the facies of contact metamorphism. This facies series is called the hornfels facies series or the contact facies series.

الصخور المتحولة Metamorphic Rocks

هى الصخور التي تتكون من الصخور الموجودة اصلاً, سابقة التكوين (نارية, رسوبية أو متحولة) نتيجة لتغير الظروف المحيطة مثل الضغط ودرجة الحرارة والمحاليل الكيميائية والتي تؤدي الي تغيير معالم ومكونات الصخر تغييراً جزئياً أو كلياً متمثلاً في عمليات إعادة التبلور وتكوين المعادن التحولية والصخر في حالة الصلابة.

تتميز مجموعة الصخور المتحولة بالخصائص الآتية:

1 - تتكون بواسطة العمليات التحوليةMetamorphic processe
وتحدث هذه العمليات في درجات حرارة مرتفعة جداً وضغط مرتفع جداً.

2 - تتكون من معادن تم إعادة تبلورها و/ أو معادن تحولية جديدة نتجت من المعادن الموجودة في الصخر الأصلي

3 - تتواجد دائماً علي شكل سهول Plains وجبال منخفضة نسبياً ممتدة لمسافات شاسعة.

4 - تحتوي علي أنسجة Textures وتراكيب Structures تحولية واضحة دالة علي العمليات التحولية.

5 - قد تحتوى علي أجزاء من الصخور الأصلية Xenoliths.

التحول Metamorphism:

هو مجموع عمليات التغير والتكيف التي تطرأ علي الصخور الصلدة في الأعماق خارج نطاق التجوية(تحت منطقة التجوية وفوق منطقة الانصهار) إستجابة لتغير الظروف الطبيعية عن تلك التي كانت سائدة أثناء عمليات التكوين, وتتمثل هذه الظروف في درجة الحرارة, الضغط والمحاليل النشطة الكيميائية والتي تعمل مجتمعة علي إعادة التبلورالجزئي أو الكامل للمعادن الأصلية أو تكوين معادن أخري أكثر ثباتاً في الظروف الجديدة مع إستحداث بنيات وأنسجة جديدة.

العوامل المؤثرة فى عملية التحول
Agents of metamorphism

ترجع عملية التحول الى تأثير مجموعة عوامل رئيسية هى :

1- درجة الحرارة Temperature
2- الضغط Pressure
3- السوائل النشطة كيميائياً
Chemically active solutions

والتي تعمل جميعها في إعتبار عاملي الزمن ونوع الصخور. تتعرض الصخور أثناء عمليات التحول الي العوامل الثلاثة مجتمعة ولكن بدرجات متفاوتة, قد تتغلب الحرارة علي الضغط او العكس, أما العامل الكيميائي فيظل فعالاً في كل الأحوال.

(أ) درجة الحرارة :Temperature

تمثل درجة الحرارة أحد أهم العوامل المؤثرة في عمليات التحول, إذ تتطلب هذه العمليات دائماً درجات حرارة في المدي الذي يمتد من الحدود العليا لعمليات التجويةWeathering, التحورDiagenesis, وفعالية السوائل الحرمائيةHydrothermal Active solutions(100-250 c)الي الحدود السفلي لعملية إنصهار الصخور Rock melting (650-800 c).

تأتى هذه الحرارة من مجموعة مصادررئيسية:

(1) اقحام الاجسام النارية بواسطة الصهير المندفع أثناء العمليات النارية.
(2) نتيجة العمق الذي تدفن فيه الصخور(المعروف أن درجة الحرارة تزداد بزيادة العمق بمعدل يعرف بالتدرج الحراري ويبلغ متوسطه في الجزئ العلوي من القشرة الأرضية 30 c لكل كيلوميتر).
(3) أو نتيجة الحركة والاحتكاك الشديد خلال عمليات التشوه (البانية للجبال).
(4) النشاط الاشعاعي.

(ب) الضغط : PRESSURE

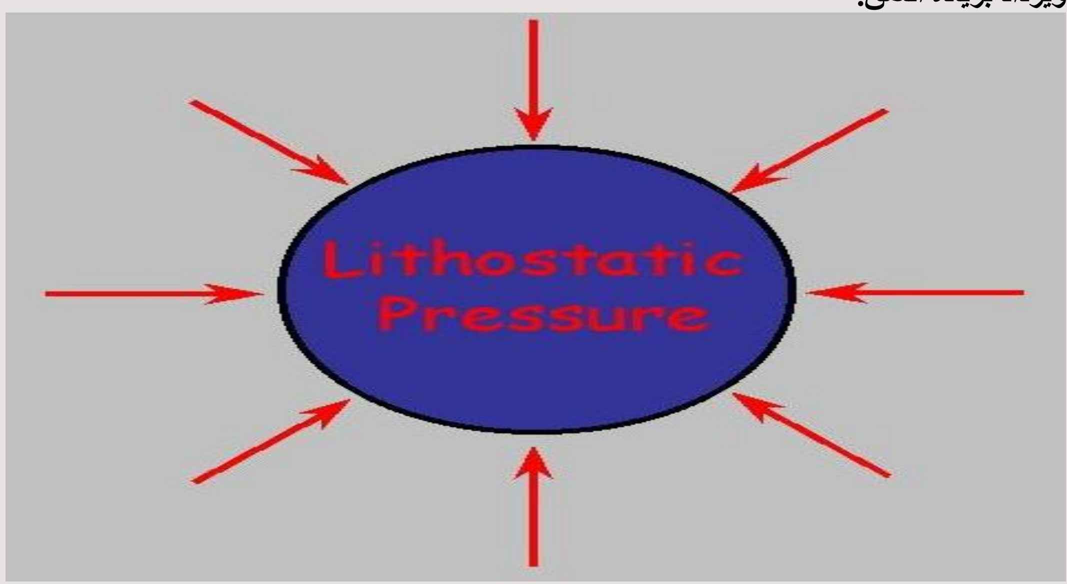
يأتي الضغط المؤثر في العمليات التحولية من القوة الناتجة من ثقل مادة الغطاء الصخري أو تلك التي تنشأ من القوة المسببة للتشوه مثل حركة الصخور أثناء الحركات الأرضية (عمليات بناء الجبالOrogeny). يزداد الضغط مع زيادة العمق مثله مثل الحرارة (300 ضغط جوي لكل 3 كلم) ويؤدي الضغط في معظم الأحيان الي تغير البنيات والأنسجة الأصلية للصخور.

يحلل الضغط عادة الى نوعيين:

(i) الضغط المنتظم غير الموجه (ضغط اللاتجاهى)

Uniform hydrostatic, Load Pressure

وهو الضغط الناشئ من ثقل الغطاء الصخري ويؤثر في المواد السائلة والصلبة ويؤدي الي تغيير الحجم ويزداد بزيادة العمق.



(ii)الضغط الموجه غير المنتظم (ضغط الاتجاهى) -Non uniform (Directed) Pressure

وهو الضغط الناشئ من حركة الصخور (شد وإنكماش) وانضغاطها مع بعضها البعض ويكون ملحوظاً بدرجة كبيرة في عمليات بناء الجبال Orogeny ويؤدي الي الاجهاد Stress في الصخور فتنفعل Strain فيؤدي الي تغيير في الشكل والحجم فيما يعرف بعملية التشوهDistortion . تنقسم الصخور من حيث استجابتها للضغط الي:* صخور قابلة للتمددElastic , * صخور مرنة Plastic ,* صخور هشة Brittle .



(ج) السوائل النشطة كيميائياً: Chemically active solutions

هذه تشكل أكثر العوامل أهمية وأكثرها حضوراً في عمليات التحول وتؤدي دوراً هاماً أما بتنشيط التفاعلات الكيميائية أو باضافة وأخذ مواد من والي الصخور أو الأثنيين معاً مما يساعد في عملية التحول .

السوائل النشطة في عمليات التحول عبارة عن محاليل مائية متأينة يشكل الماء الجزء الأهم ويأتي من الماء المحبوس في الفراغات البينية في الصخور أو ذلك الموجود كجزئ من البنية الهيكلية للمعادن المكونة للصخور أو مع السوائل الهاربة من تبلور الصهير . أما السوائل الأخري هي حامض الكربونيك,الأحماض الهالوجينية, مركبات الكبريت ومحاليل أخري ذات أصل بركاني

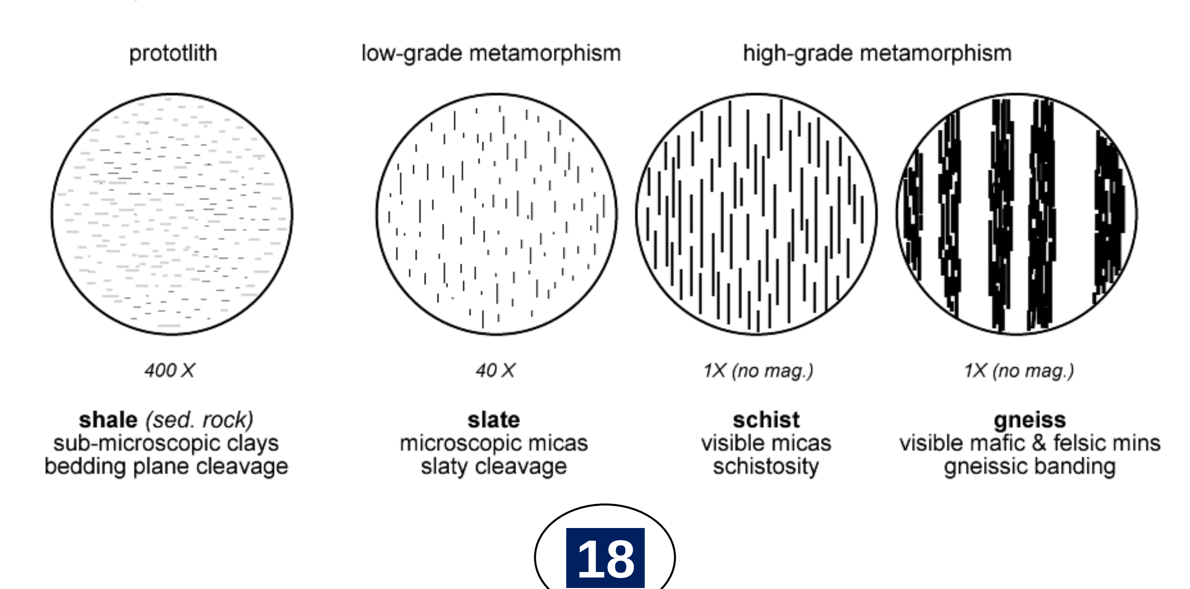
Types of metamorphism:

Regional metamorphism:

Regional or Barrovian metamorphism covers large areas of continental crust typically associated with mountain ranges, particularly subduction zones or the roots of previously eroded mountains. Conditions producing widespread regionally metamorphosed rocks occur during an orogenic event. The collision of two continental plates or island arcs with continental plates produce the extreme compressional forces required for the metamorphic changes typical of regional metamorphism. These orogenic mountains are later eroded, exposing the intensely deformed rocks typical of their cores. The conditions within the subducting slab as it plunges toward the mantle in a subduction zone also produce regional metamorphic effects. The techniques of structural geology are used to unravel the collisional history and determine the forces involved. Regional metamorphism can be described and classified into metamorphic facies or metamorphic zones of temperature/pressure conditions throughout the orogenic terrane.

Regional Metamorphism is the result of high pressures and elevated temperatures associated with deep burial in an orogenic belt. Platy minerals (micas) and elongate minerals (hornblende) recrystallize and/or rotate into a new orientation perpendicular to the applied stress, while other minerals recrystallize into new crystals which are stable at the higher pressures and temperatures.

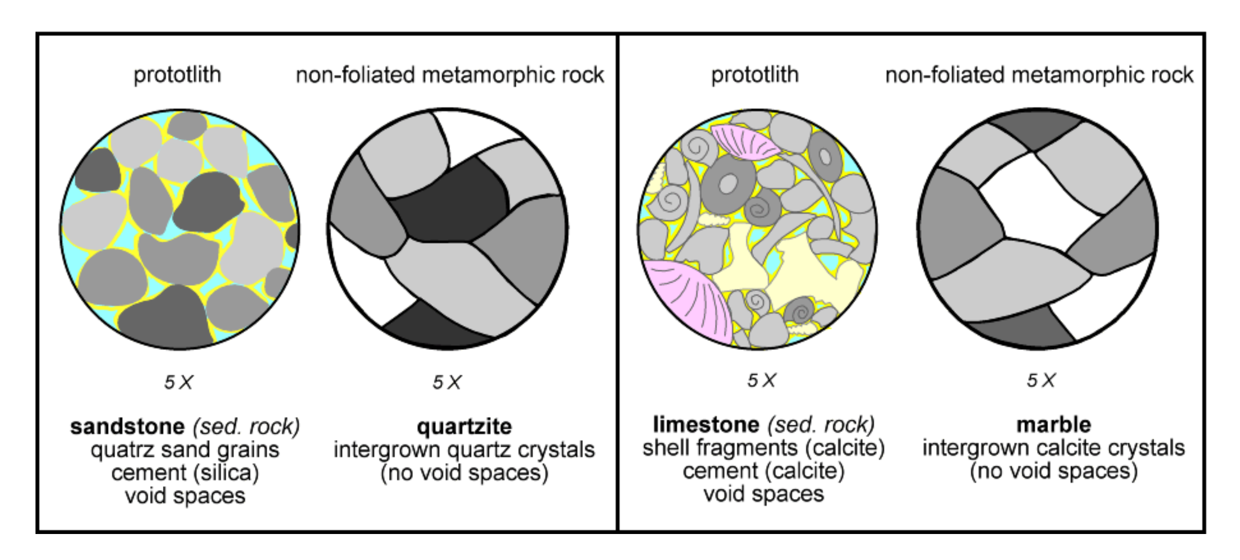
Foliation is the result of the parallel arrangement of (micas, etc.) in a plane perpendicular to the maximum principal applied stress. A lineation is caused by a similar growth of elongate minerals (eg. hornblende) in this plane. **Slate, schist, and gneiss** are three common foliated metamorphic rocks. **Slate** is a hard, fine-grained rock with a well-developed rock cleavage or slaty cleavage caused by the incipient growth of platy (micaceous) minerals, due to metamorphism of fine-grained clastic sediments such as shale and siltstone and also volcanic tuffs. **Schist** is a still higher degree of metamorphism, characterized by coarse grained foliation and/or lineation, with mica crystals large enough to be easily identified with the unaided eye. **Gneiss** is a medium to coarse-grained, irregularly banded rock with only poorly developed cleavage. The light and dark bands ***(gneissic banding)*** are alternations of felsic vs. mafic layers.



Slate is a product of ***low grade metamorphism*** (not terribly great burial temperatures and pressures are required). Schist and gneiss are produced by medium to ***high grade metamorphism***. In some cases gneisses are produced by higher grade metamorphism than schists. Low-grade metamorphic rocks tend to be fine-grained (the newly formed metamorphic mineral grains that is). High-grade metamorphic rocks tend to be coarse-grained. But grain size is also dependent on the grain size of the protolith.



Non-foliated metamorphic rocks include **quartzite**, which is metamorphosed sandstone in which the quartz grains have recrystallized into a very solid interlocking network, and **marble**, which is metamorphosed limestone composed of recrystallized and interlocking calcite or dolomite crystals.



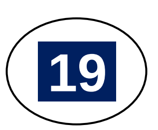
Foliation in metamorphic rocks is related to the orientation of the applied stresses and not the original sedimentary or earlier metamorphic structures. The original shale bedding ***(relict bedding)*** is sometimes preserved as color contrasts in a slate. In most cases the slate's fracture cleavage lies at some angle to the original bedding plane.

Three other types of metamorphism are important in certain tectonic environments.

Contact (thermal) metamorphism :

A metamorphic aureole in the Henry Mountains, Utah. The greyish rock on top is the igneous intrusion, consisting of porphyritic granodiorite from the Henry Mountains laccolith, and the pinkish rock on the bottom is the sedimentary country rock, a siltstone. In between, the metamorphosed siltstone is visible as both the dark layer (~5cm thick) and the pale layer below it.

Contact metamorphism occurs typically around intrusive igneous rocks as a result of the temperature increase caused by the intrusion of magma into cooler country rock.



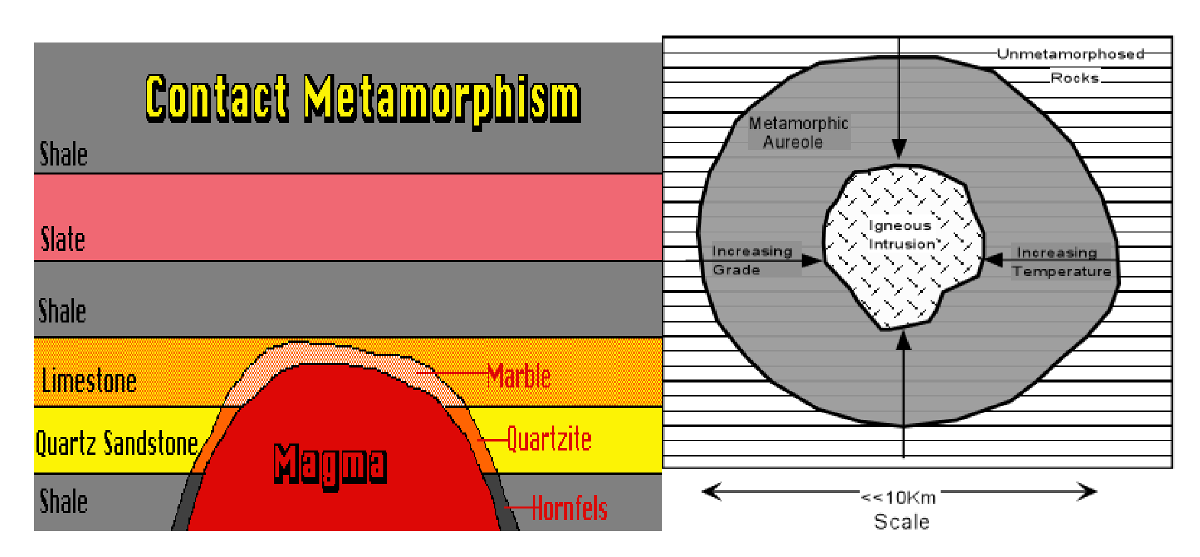
The area surrounding the intrusion where the contact metamorphism effects are present is called the *metamorphic aureole*. Contact metamorphic rocks are usually known as hornfels. Rocks formed by contact metamorphism may not present signs of strong deformation and are often fine-grained.

Contact metamorphism is greater adjacent to the intrusion and dissipates with distance from the contact. The size of the aureole depends on the heat of the intrusion, its size, and the temperature difference with the wall rocks. Dikes generally have small aureoles with minimal metamorphism whereas large ultramafic intrusions can have significantly thick and well-developed contact metamorphism.

The metamorphic grade of an aureole is measured by the peak metamorphic mineral which forms in the aureole. This is usually related to the metamorphic temperatures of pelitic or alumonisilicate rocks and the minerals they form.The metamorphic grades of aureoles are andalusite hornfels, sillimanite hornfels, pyroxene hornfels.

Magmatic fluids coming from the intrusive rock may also take part in the metamorphic reactions. Extensive addition of magmatic fluids can significantly modify the chemistry of the affected rocks. In this case the metamorphism grades into metasomatism. If the intruded rock is rich in carbonate the result is a skarn. Fluorine-rich magmatic waters which leave a cooling granite may often form greisens within and adjacent to the contact of the granite. Metasomatic altered aureoles can localize the deposition of metallic ore minerals and thus are of economic interest.

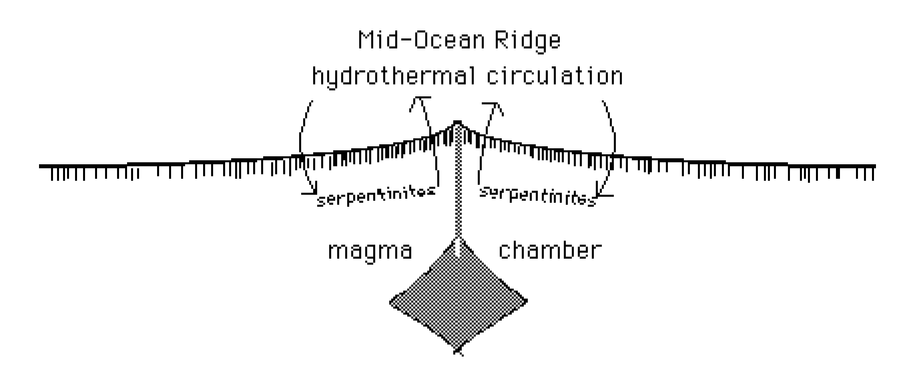
Contact Metamorphism is the result of baking the surrounding **country rocks** by an igneous intrusion. The **metamorphic aureole** surrounding an igneous body may be only 2 centimeters wide adjacent to a small dike or it may be 2 kilometers wide at the contact with a large, slow-cooling granite pluton. Contact metamorphosed rocks may be bleached out looking and non-descript fine-grained. A common contact metamorphic rock is *hornfels* (German for "hard rock").



Hydrothermal metamorphism:

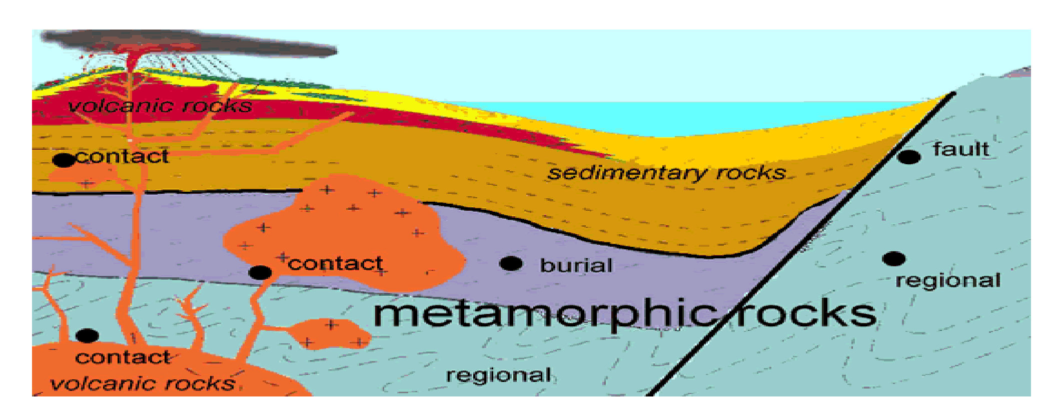
Hydrothermal metamorphism is the result of the interaction of a rock with a high-temperature fluid of variable composition. The difference in composition between existing rock and the invading fluid triggers a set of metamorphic and metasomatic reactions. The hydrothermal fluid may be magmatic (originate in an intruding magma), circulating groundwater, or ocean water. Convective circulation of hydrothermal fluids in the ocean floor basalts produces extensive hydrothermal metamorphism adjacent to spreading centers and other submarine volcanic areas. The fluids eventually escape through vents in the ocean floor known as black smokers. The patterns of this hydrothermal alteration is used as a guide in the search for deposits of valuable metal ores.

Hydrothermal alteration, sometimes considered a form of metamorphism, is related to the circulation of hot, mineral-laden fluids through rock bodies. This is particularly important in alteration of ocean crust in the high heat flow regime near the mid-ocean ridges. **Serpentinites** form from the hydration of peridotites, olivine rich rocks at the base of the oceanic crust. Hydrothermal alteration also occurs as a result of hot fluids escaping from a cooling pluton, in addition to the high-temperature contact metamorphism occurring there.



Shock metamorphism :

This kind of metamorphism occurs when either an extraterrestrial object (a meteorite for instance) collides with the Earth's surface or during an extremely violent volcanic eruption. Impact metamorphism is, therefore, characterized by ultrahigh pressure conditions and low temperature. The resulting minerals (such as SiO_2 polymorphs coesite and stishovite) and textures are characteristic of these conditions.



Dynamic metamorphism :

Dynamic metamorphism is associated with zones of high to moderate strain such as fault zones. Cataclasis, crushing and grinding of rocks into angular fragments, occurs in dynamic metamorphic zones, giving cataclastic texture.

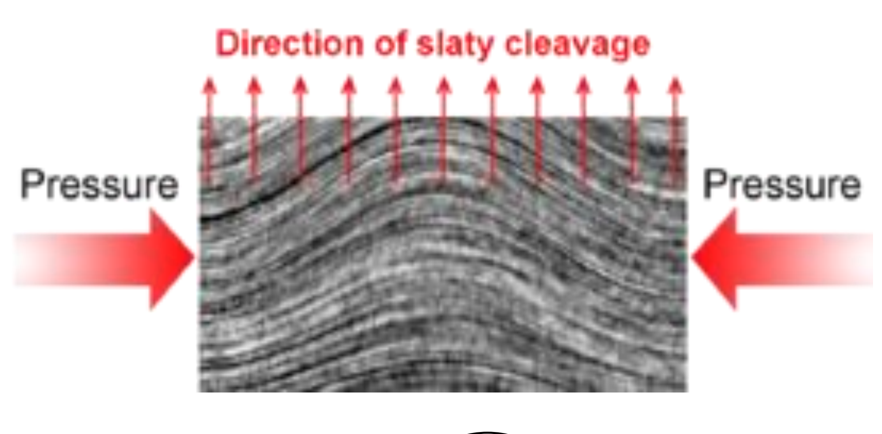
The textures of dynamic metamorphic zones are dependent on the depth at which they were formed, as the temperature and confining pressure determine the deformation mechanisms which predominate. Within depths less than 5 km, dynamic metamorphism is not often produced because the confining pressure is too low to produce frictional heat. Instead, a zone of breccia or cataclasite is formed, with the rock milled and broken into random fragments. This generally forms a mélange. At depth, the angular breccias transit into a ductile shear texture and into mylonite zones.

Within the depth range of 5–10 km pseudotachylite is formed, as the confining pressure is enough to prevent brecciation and milling and thus energy is focused into discrete fault planes. Frictional heating in this case may melt the rock to form pseudotachylite glass.

Within the depth range of 10–20 km, deformation is governed by ductile deformation conditions and hence frictional heating is dispersed throughout shear zones, resulting in a weaker thermal imprint and distributed deformation. Here, deformation forms mylonite, with dynamothermal metamorphism observed rarely as the growth of porphyroblasts in mylonite zones.

Overthrusting may juxtapose hot lower crustal rocks against cooler mid and upper crust blocks, resulting in conductive heat transfer and localised contact metamorphism of the cooler blocks adjacent to the hotter blocks, and often retrograde metamorphism in the hotter blocks. The metamorphic assemblages in this case are diagnostic of the depth and temperature and the throw of the fault and can also be dated to give an age of the thrusting.

Cataclastic metamorphic rocks form where rocks are being faulted and sheared. Cataclasite or fault breccias form in brittle fault zones and consist of larger angular rock fragments dispersed in a fine-grained matrix**.** Mylonites are foliated, actually sheared, stretched, and streaked rocks, formed in plastic shear zones, at depths and pressures too great for rock to break**.** The rock becomes drawn out like modeling clay or bubble gum.



Types of metamorphism: أنواع التحول

يتم التحول في سلسلة من العمليات المعقدة والمتنوعة تسمي بالعمليات التحولية, قد تكون التحولات واسعة النطاق أو ضيقة إعتماداً علي عوامل التحول والبيئة الجيولوجية التي تتم فيها هذه العمليات وعليها يمكن تقسيم التحول الي الأنواع التالية:

(1) التحول الحراري (التماسي).Thermal (contact) metamorphism
(2) التحول الديناميكي (التحطيمي) . Dynamic (cataclastic) metamorphism
(3) التحول الاقليمي (الحراري- ضغطي) .Regional (dynamo-thermal) metamorphism
(4) التحول التصادمي .Impact (shock) metamorphism
(5) التحول الدفني Burial metamorphism

(1) التحول الحراري (التماسي) Thermal (contact) metamorphism

يعتبر هذا النوع من التحولات ضيقة النطاق ويتم محلياً في مناطق تداخل الكتل الصهيرية في صخور مضيفة سابقة التكوين, وتكون الحرارة المتولدة من الصهير العامل المسيطر في هذا النوع مع عدم إغفال دور الغازات والسوائل في اتمام التحول.

يسمي النطاق المتأثر بالتحول والذي يمتد من عدة أقدام الي عدة كيلومترات بإسم دائرة التحول Contact aureole, ويكون التأثير الحراري علي أشده في مناطق التماس المجاورة للكتلة الصهيرية المتداخلة ويقل تدريجياً بعيداً من منطقة التماس.

هنالك مجموعة من العوامل التي تعمل علي تحديد التأثير الحراري علي الصخور وبالتالي تتحكم في درجة تحول الصخور ومدى إنتشارها وهي:

(i) حجم الصهيرالمتداخل: تتسع دائرة التحول كلما كانت الكتل المتداخلة كبيرة الحجم,كما هو الحال في دوائر التحول حول الكتل البلوتونية والباثوليتية.

(ii) درجة حرارة الصهير: تكون درجة التحول عالية إذا كانت حرارة الصهير مرتفعة جداً وإذا كانت الظروف المحيطة تعمل علي تبريد الصهير ببطئ.

(iii) التركيب الكيميائي للصهير: كلما زادت حموضة الصهير زاد التأثير علي تحول الصخور وذلك لأن الصهير الحمضي يكون محملاً بكميات كبيرة من الغازات والسوائل النشطة كيميائياً.

(iv) التركيب المعدني للصخور: تؤثر نوعية الصخر علي درجة التحول ونوعه ونوع النواتج صخرية, مثال: حجر رملي Sandstone يتحول الي كوارتزيت Quartzite, صخور طينية Mudstone تتحول الي هورنيفلس Hornefels, صخور جيرية Limestone تتحول الي رخام Marble.

تنتج من التحول الحراري (التماسي) مجموعة صخور كتلية massive

rocks ذات معادن غير موجهة مثل الرخام Marble, الهورنيفلس Hornefels و الكوارتزيت Quartzite .

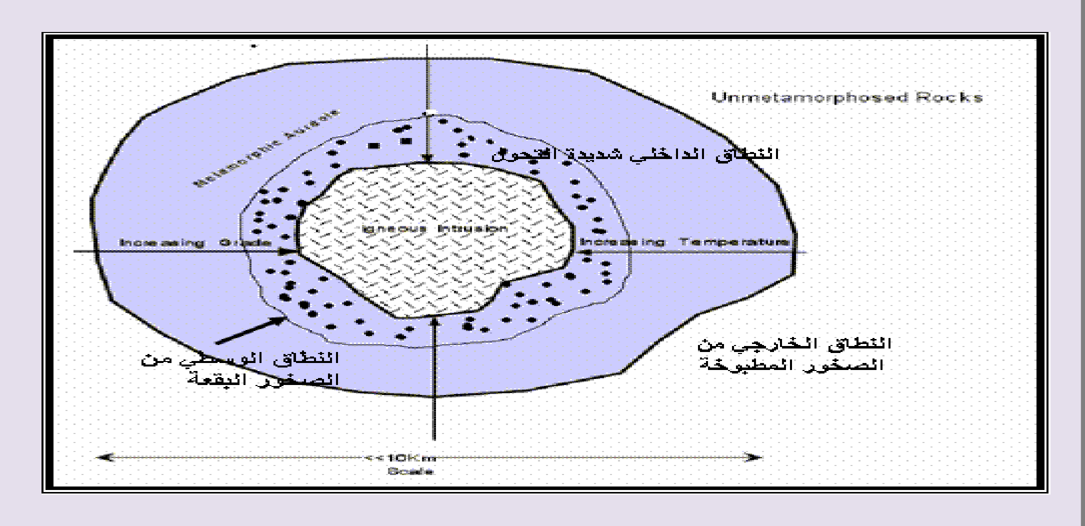
تعد الحرارة العامل الرئيس في هذا النوع من التحول ويكون للضغط تأثير ثانوي، وهو على عدة أشكال أهمها الحراري (Thermal Meta.) ويطلق هذا الاصطلاح على جميع التغييرات التي تكون فيها الحرارة العامل الرئيس، أما اصطلاح (PyroMeta.) يشير إلى التحولات التي تحدث في درجات الحرارة العالية والذي يحصل على حدود التماس المباشر ما بين الصخور المجاورة أو المحيطة بالصهارة (الماجما)، وكذلك يحدث في الصخور المطمورة في الصهارة.

التحول الكاوي (Caustic Meta.) يطلق على التحولات التي تحدث في الصخور بصورة سريعة عند تماسها بالصهارة أو الأجسام النارية الجوفية الحارة وتؤدي إلى احتراق (Burning) الصخور أحيانا أو تحولها إلى زجاج بركاني. واصطلاح التحول التماسي (Contact Meta.) يصف تحولا يحدث حول الكتل النارية الكبيرة وفي درجات حرارة واطئة نسبيا بالمقارنة مع سابقه بحيث يحدث تغير ملحوظ بالصخرة، إذ أن الانبثاقات الصخرية تزيد من الانتقالية الجزيئية للمحاليل البينية وبذلك تزيد من عملية تحول المعادن الصخرية.أما اصطلاح (Pneumatolitic Meta) أو(Additive Meta.) فهو تحول يسبب تحول كلي في تركيب الصخرة.

التحول الحراري أو التماسي: Thermal or Contact Metamorphism

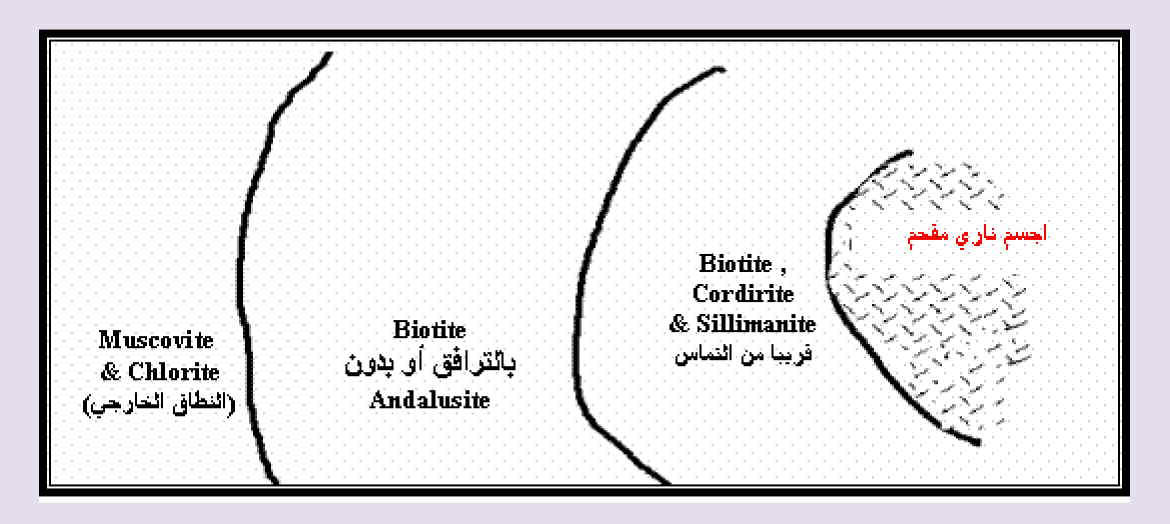
تلعب الاقحامات النارية (igneous rocks) دورا مهما في حدوث التحول التماسي للصخور وذلك من خلال تزويد الصخور المجاورة للمقحم الناري بالحرارة والمحاليل الساخنة. وتقل التأثيرات التحولية حول المقحمات النارية بصورة سريعة بعيدا عن الجسم الناري وذلك لقلة انتشار الحرارة، ولقد وجد أن الإقحام الجرانيتي يكوّن هالات تماسية (Contact aureoles) واضحة ومميزة في الحقل وأكثر عرضا من تلك المتكونة حول الاقحامات القاعدية والصخور الجابروية مع العلم أن الصخور القاعدية والجابروية تمتلك حرارة أعظم من الصخور الجرانيتية، واحد أهم العوامل المؤدية إلى هذا التباين في عرض الهالات التماسية هو أن الصهير الجرانيتي المقحم خلال الصخور المجاورة country rocks يكون حاملا للسوائل والمحاليل أكثر مقارنة بالصهير القاعدي حيث يقوم الماء والمحاليل النشطة الحارة بنقل الحرارة والايونات وبذلك تساعد في عملية التبلور.

الترتيب المتسلسل في الصخور المجاورة غير المتحولة إلى الصخور الهورنفلسية الأكثر تحولا يسمى بالتحول ألتقادمي (Progressive metamorphic sequence).



الهالة التماسية لأحد الأجسام النارية

ويمكن ملاحظة تسلسلات معدنية ونسيجية مهمة في هذا التسلسل ويحصل هذا النوع بصورة واضحة عادة في الصخور الطينية (Pelitic Rx.) ويكون التغير المعدني من الخارج إلى الداخل كما في الشكل أدناه:

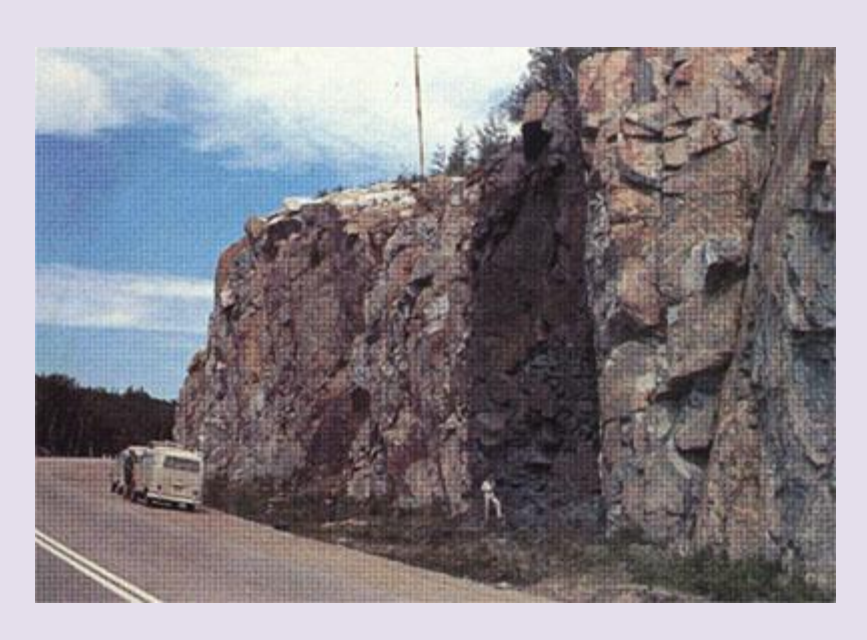


[سلسلة التحول ألتقادمي للصخور المجاورة لجسم ناري]

تظهر الهالات في الصخور الكلسية تغيرا على نطاق واسع لكن اقل انتظاما لان المحتوى المائي في هذه الصخور ينقل إليها بعض المواد من الصهارة والتي تؤثر على درجة انتظام الهالة والتمنطق يكون غير واضح وعلى نطاق محدود، درجات التحول للصخور المحيطة بالجسم الناري والذي هو في طور التبريد تعتمد على شكل الجسم الناري وحجم ذلك الجسم وكذلك على خواص الصخور المحيطة أو المخترقة من قبل هذا الجسم ومحتواها من السائل وكذلك نفاذيتها، فإذا كان المحتوى لهذه الصخور قليلا ونفاذيتها ليست جيدة ومستويات التطبق فيها ليست ذات أهمية فسريان الحرارة فيها (heat flow) سيكون من النوع الايصالي (conductive)، أما إذا كان محتوى الماء في هذه الصخور عال عند ذلك تسمح بنقل الحرارة ونقل الحرارة في مثل هذه الحالة يصبح من نوع (convective) بطريقة الحمل أي أن الانتقال ليس للحرارة فقط وإنما للمواد المذابة في السوائل المتحركة circulation fluids، ولوحظ من بعض المخططات الخاصة انه في النماذج للحرارة الموصلة المنتشرة حول جسم ناري مستقر أو ساكن أن درجة الحرارة القصوى في الصخور المحيطة بجسم ناري تكون تقريبا نصف درجة حرارة الصهير (حرارة الجسم الناري المخترقة) ولكنها تعتمد أيضا على درجة حرارة الصخور قبل الإقحام.

إذا كان الجسم الناري المقحم كبيرا نوعا ما فأن ارتفاع درجات الحرارة في الصخور المجاورة سوف يستمر لفترة طويلة كافية لحدوث التفاعلات الكيمائية. أما الصخور المجاورة لجسم صغير كالسدود القاطعة **dikes** أو الجدد **sills** فقد لا تتعرض لهذه الظروف ولكنها قد تسخن وتطبخ **baked** وتصبح صلبة مع احتمالية تبلور المواد البينية الرابطة **Cementing materials** إذا كانت الصخور الصلبة.

أن كثيرا من الاقحامات النارية تقوم بتزويد الصخور المجاورة بمحاليل ساخنة عند تبلورها وانخفاض درجات حرارتها حيث تستطيع هذه السوائل أن تلعب دورا مهما في تكون معادن جديدة أو مناطق تمعدن **mineralization zones** قد تحتوي على معادن اقتصادية.



جسم ناري عمودي Dike منكشف محاط بصخور متحولة حراريا

2.التحول السائد بالضغط الموجه(التحول التحطيمي):

Directed Pressure Meta.

(Cataclastic Meta.)

وهو تحول ينتج عنه تشويه تحطيمي للصخر بفعل الضغط الهيدروستاتيكي الساكن (Hydrostatic Pressure) أو الإجهاد (stresses)، فمن المعروف أن الإجهاد يعمل عادة باتجاه معين وبوجود قليل من الحرارة أو بدونها فان تأثيرها في مثل هذه الحالة هو سحق الحبيبات الصخرية وتهشيمها وذلك من خلال التحرك القوي من خلال التحرك القوي لكتل الصخور وتتكون قليل من المعادن التي قد تترتب بأشكال متوازية أو بهيئة بنيات شريطية متوازية (Parallel bands structures) على امتداد مستويات الحركة الداخلية.

. التحول السائد بالضغط الموجه والحرارة: Directed Press. & Heat Pred. Meta. غالبا ما يتحد العاملان في عمليات تحول الصخور، فهما العاملان الأهم في عمليات تحول الصخور وإنتاج بنيات بلورية جديدة لتلك الصخور بنفس الوقت، ومن أشكاله:

1) ***التحول الديناميكي الضغطي*** *Dynamothermal Meta.* : عندما يكون الضغط الموجه هو العامل الرئيس المؤثر وهذا الضغط يعمل على خفض درجة انصهار المعادن موقعيا ، والذي ينتج بسبب حركات الرفع الأرضية المسؤولة عن تكوين الجبال ويحصل في مناطق الطيات الأرضية ويمتد لمسافات كبيرة مساحيا ومن أهم الأنواع الصخرية التي تنتج عن هذا النوع من التحول صخور الشيست (Schist) والنايس (Gniess) .

2) ***تحول الحمل أو الانطمار*** _ *Loud or Burial Meta.* : يحدث بسبب الضغط الناتج عن عمود الصخور مع وجود درجات الحرارة العالية المتزايدة مع الأعماق فضلا عن تأثير المحاليل الكيميائية.

3) *التحول الاستاتيكي* _ *Static Meta.*: وهو تحول واطئ يحدث عند درجات الحرارة الواطئة وبوجود الماء في الأعماق القليلة ويتداخل أحيانا مع عمليات التصخر والتحجر وحتى عمليات التلاحم.

. **التحول السائد بالضغط المنتظم والحرارة. Undirected Press.& Heat Pred. Meta.**

يحصل بفعل كل من درجة الحرارة والضغط ويحدث في ظروف الأعماق حيث يقل دور الضغط الموجه، وفي هذا النوع من التحول تكتمل تحولات المعادن حيث لا تظهر بنيات جديدة بصورة كبيرة. والمعادن الجديدة المتكونة بسبب هذا النوع من التحول تكون ذراتها متراصة في حجوم اصغر وذات وزن نوعي اكبر مثل صخور (Eclogite) و(Scharnogite) *وهما ذاتا نسيج حبيبي متساوي مكونة ما يعرف بـ*(Granulite)، كما يسمى هذا التحول أحيانا بالتحول الجوفي (Plutonic Meta.) .

3) التحول الاقليمي (الضغطي - الحراري) Regional (dynamo-thermal) metamorphism

من التحولات واسعة النطاق ويحدث فيه تغيير وتكييف الصخور سابقة التكوين في مناطق أقليمية شاسعة تمتد لآلاف الكيلومترات المربعة وبسمك تقدر بآلاف الامتار تحت تأثير الضغط العالي المصحوب بارتفاع كبيراً جداً في درجة الحرارة, كما أن وجود المحاليل النشطة كيميائياً تساعد كثيراً في عملية التحول, يأتي هذا الضغط من حركات القشرة الأرضية ونتيجة الدفن لإعماق بعيدة في باطن الأرض.
تصاحب هذا النوع من التحولات إعادة تبلور المعادن الأصلية الموجودة سابقاً وتكوين معادن جديدة وذلك بتفتت وتكسر المكونات المعدنية للصخور وأحياناً قد تنصهر وتذوب ثم تستعيد كيانها من جديد متبلورة ومصفوفة بحيث تشغل أقل حيز ممكن تحت تأثير الضغط.

كما ويصاحب هذا التحول تكوين بنيات وأنسجة تحولية جديدة وذلك بترتيب المعادن التحولية المتكونة حديثاً في نظام يناسب الظروف المستجدة, ويتم هذا الترتيب بحيث يكون المحور الطولي لبلوراتها في إتجاه واحد عمودي علي اتجاه الضغط وينشأ عن هذا الترتيب تجمع معدني في هيئة طبقات رقيقة أو شرائط **Bands** , وريقات **Folia** ورقائق أو صفائح **Laminae** متوازية ومتعامدة علي اتجاه الضغط.

4- تحول الصدمة Shock Meta.

وهو تحول طبيعي يحدث للصخور نتيجة سقوط النيازك على سطح الأرض مما يتسبب في حدوث تغييرات صخرية تتركز بالقرب من منطقة سقوط النيازك **meteorites**، وهذه التغييرات تتناسب مع كتلة النيزك وقوة ارتطامه بالأرض والذي يسبب اهتزازات قوية بالقرب من مركز السقوط ولكنها تتلاشى تقريبا كلما ابتعدنا عن مركز سقوط النيزك على شكل انطقة تحولية متدرجة .

5- التحول الديناميكي أو الحركي: Dynamic Metamorphism

1.التحول الديناميكي الطبيعي:

هذا النوع من التحول يحدث في مناطق محدودة المساحة والحجم إذ تكون هذه الصخور محصورة ضمن انطقة ضيقة قريبة من انطقة الفوالق ومستويات الانزلاق Major faults &thrust zones، وأظهرت الدراسات أن هذا النوع من التحول يحدث في نفس الوقت الذي تحدث فيه حركة على سطوح الفوالق والانزلاقات ويؤدي الجهد الشقي العالي high shear stress في انطقة الفوالق إلى سحق الصخور على طول مستوياته.

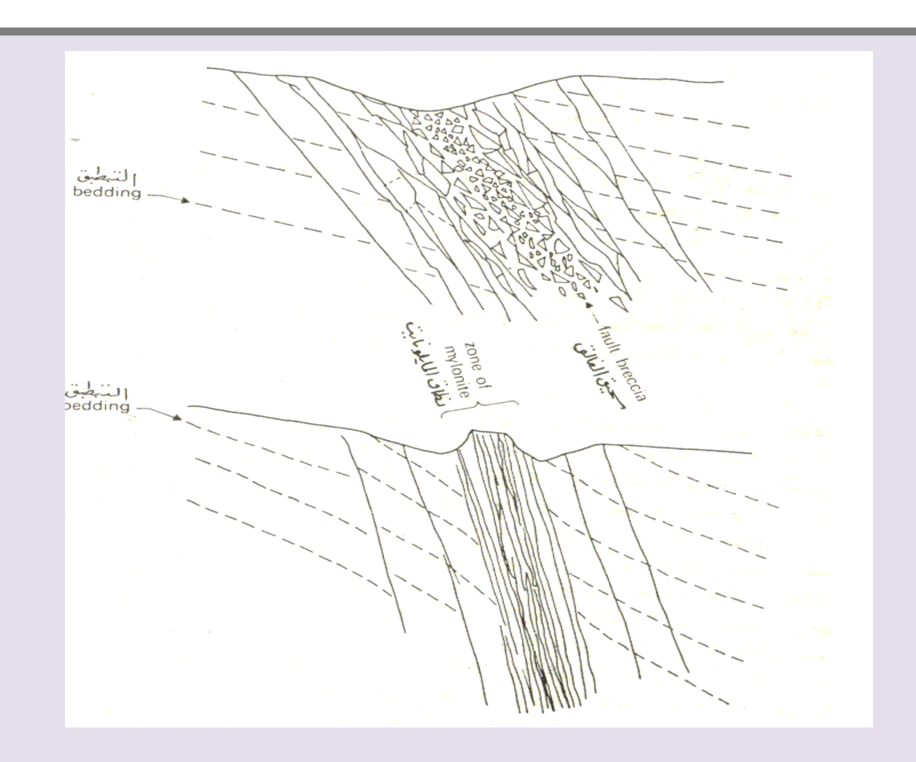
يمكن ملاحظة أن هنالك اختلافات بين العمليات المؤدية إلى التحول الحركي من جهة والعمليات المؤدية إلى التحول التماسي، وفي بعض المناطق الضحلة وفي صخور هشة نسبيا نلاحظ انه يحدث تكسر وسحق كبير لهذه الصخور بمقياس يمكن ملاحظته بالعين المجردة بينما في مناطق أكثر عمقا من القشرة الأرضية تحدث الحركة في انطقة ضيقة على سطوح الفوالق والانزلاق فيحدث تبلور أحيانا أو يحدث انصهار جزئي في حالات أخرى (partial melting) وهذه العمليات بمجموعها تعطي ناتج من الصخور يسمى المتحولة حركيا أو ديناميكيا.

من الأدلة المهمة على حصول حركة ضمن فالق معين أو كسر أو انزلاق معين هو وجود ما يسمى بـ (fault breccia) وهي عبارة عن نواتج تكسر الصخور بسبب عمليات الانزلاق والتصدع وفيما بعد عملية السحب، وأحيانا لا يلاحظ وجود هذه المواد بل يتواجد بدلا عنها ما يشبه المسحوق الصخري الناعم (Micro breccia) ويختلط هذا المسحوق مع أرضية الصخورRock floor.

عندما تكون الحركة كبيرة وعلى مساحة واسعة وعمق لا بأس به بحيث أن جدران الفالق سوف تضغط على بعضها البعض الأخر فالتحول سيكون كبير جدا في هذه الحالة وسيشتمل كذلك على تحول الأجزاء المتكسرة والأرضية الموجودة على السطح حيث يحدث تغير موضعي في الصخور المجاورة، فمثلا الصخور الكتلية (الكوارتزايت) والحجر الجيري تحت ظروف معينة تعطي ناتجا معينا دقيق الحبيبات تسمى بالمايلونايت (Mylonite) الذي يتكون من حبيبات تشبه العدسات مع الصخور المحيطة بها وهو دليل على التحول المضطرب أو التشويهي.

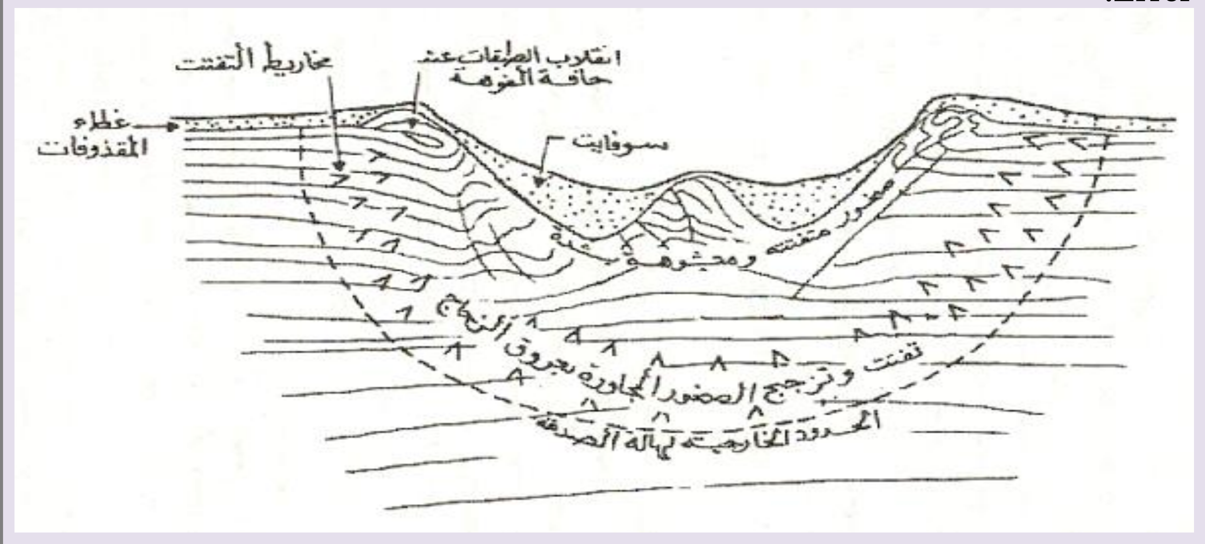
أما إذا تكونت الأجزاء المتكسرة من الصخور المجاورة من نوع واحد من البلورات فان ذلك يعطي الصخور نسيجا يسمى (porphyritic or porphyroclast texture)، أما إذا كانت الصخور المجاورة عبارة عن shale أو صخور متحولة أصلا مثل slate or schist تحتوي على المعادن الورقية Mica minerals فان هذه المعادن ستترتب بشكل مواز لسطح الكسر فتكون ما يسمى Phylonite أو tectonic slate . ومعناها أن هذه الصخرة تأثرت بالحركة النسبية للفالق والمعادن تكون موجهة باتجاه مواز لمستوى الفالق، وفي هذه الحالة فان هذه الصخرة لا تمتلك البنية السابقة porphyritic tex. لأنها تكون متورقة باتجاه وليست حبيبية.صخور المايلونايت والفايلونايت تمتلك نسيجا تخطيطيا Lination واتجاه هذا التخطيط بالمجهر يعطينا فكرة عن اتجاه الحركة خلال فترة تكون كلا النوعين من الصخور.

تتحكم بالتحول الحركي عدة عوامل أهمها شدة واتجاه الحركة على سطح الفوالق والتي تؤدي إلى ما يسمى بالتشويه Distortion وكذلك عوامل الضغط والحرارة ومكونات الصخر الأصلي.



التحول الديناميكي في مناطق التفلق الصخري ومستويات الانزلاق

Error!



انطقة التحول الصخري الناتج عن التحول الديناميكي الطبيعي اثر سقوط نيزك على سطح الأرض

2. التحول الديناميكي الاصـــطناعي: Artificial Dyn.Meta. : تحول يحدث نتيجة تدخل الإنسان بفعل التجارب التي يجريها وتحديدا التجارب النووية تحت السطحية حيث تعاني الصخور القريبة لمنطقة التجربة من التكسرات بفعل التموجات والاهتزازات الصادرة عن مركز الانفجار وقد تتحول بعض الصخور وخاصة في المناطق ذات التماس المباشر مع منطقة التجربة إلى مسحوق ناعم جدا. وهذا التحول يعتمد على قوة التفجير والبعد عن السطح ومكان التفجير فضلا عن نوعية الصخور التي تعاني من هذا النوع من التحول.

نسبة للتركيب الكيميائي:

According to Chemical Composition

عمليات التحول تقسم حسب التغييرات التي تحدث في التركيب الكيميائي للصخور نتيجة وأثناء عملية التحول إلى نوعين رئيسين وهما:_

أ. التحول الاعتيادي أو المتماثل كيميائيا: Normal or Chemical Meta.

هذا النوع من التحول يمتاز بعدم حدوث أي تغيير في التركيب الكيميائي للمعادن المكونة للصخرة قبل وبعد التحول، وكل ما يحدث هو إعادة تبلور للمعادن المكونة للصخرة الأصلية أو تغير بسيط لهذه المعادن.كما هو الحال في صخور الحجر الجيري (Limestone) المتبلورة إلى صخور المرمر(Marble).

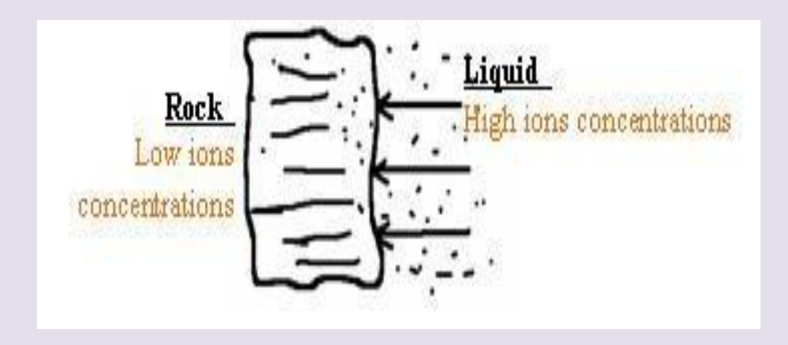
ب. التحول المتغير كيميائيا أو الاحلالي أو الميتاسوماتي: Allochemical or Metasomatic

Meta. يرافق هذا التحول حدوث تغير في التركيب الكيميائي الكلي للصخر، وذلك من خلال حصول إضافة أو فقدان في بعض العناصر المكونة للمعادن التي تكون الصخرة الأصلية قبل عملية التحول، وعملية الإضافة والفقدان هذه تتم بإحدى الحالات التالية:

1- الإحلال بالحالة الغازية _ *Metasomatism in gas phase:* يتم في هذه العملية انتقال العناصر والايونات سواء كإضافة أو فقدان من خلال الغازات والأبخرة المنبعثة المرافقة للانبعاثات والانفجارات النارية واهم هذه الغازات والأبخرة: H_2O, CO_2, H_2S,NO_2,SO_2 .

2- الإحلال في الحالة السائلة _ *Metasomatism in liquid phase:* وتتمثل هذه الحالة من خلال انتقال العناصر والايونات الذائبة في المياه الحارة ولهذا فأن هذا النوع من التحول يسمى أيضا بالتحول الحرمائي (Hydrothermal Meta.) ، كما وتنتقل هذه الايونات من خلال سوائل أخرى والتي تكون غالبا على شكل حوامض مثل (H_2CO_3, HI, HCl, H_2S) ذات الأصل البركاني.

3- الإحلال بعملية الانتشار _ *Diffusion:* وهي عملية تتم مابين الايونات المذابة في السوائل وما بين الصخور التي تمثل الحالة الصلبة والتي لا تحوي على أية شقوق أو تكسرات نتيجة لاختلاف تركيز الايونات بين الوسطين.



عملية الانتشار احد ميكانيكيات التحول الاحلالي

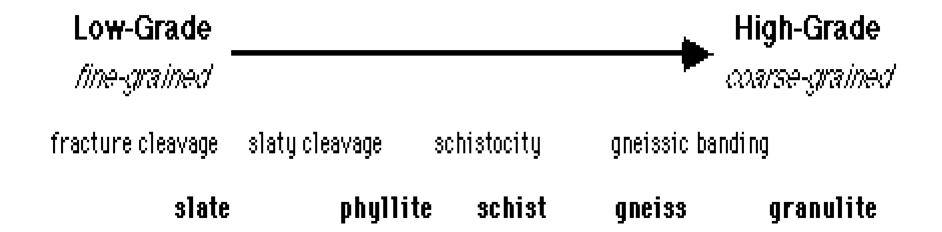
إن أهمية هذا النوع من التحول (الحرمائي) هو نشوء حالة من انتقال بعض الفلزات ذات الأهمية الاقتصادية مثل النحاس أو الرصاص أو الخارصين أو الذهب أو القصدير...الخ من الفلزات او الترسبات الاقتصادية والتي تشكل بتجمعها وتراكمه خامات معدنية اقتصادية.

CHAPTER 2

Metamorphic grades And Depth zones and metamorphism

Metamorphic grades:

In the Barrovian sequence (described by George Barrow in zones of progressive metamorphism in Scotland), metamorphic grades are also classified by mineral assemblage based on the appearance of key minerals in rocks of pelitic (shaly, aluminous) origin:

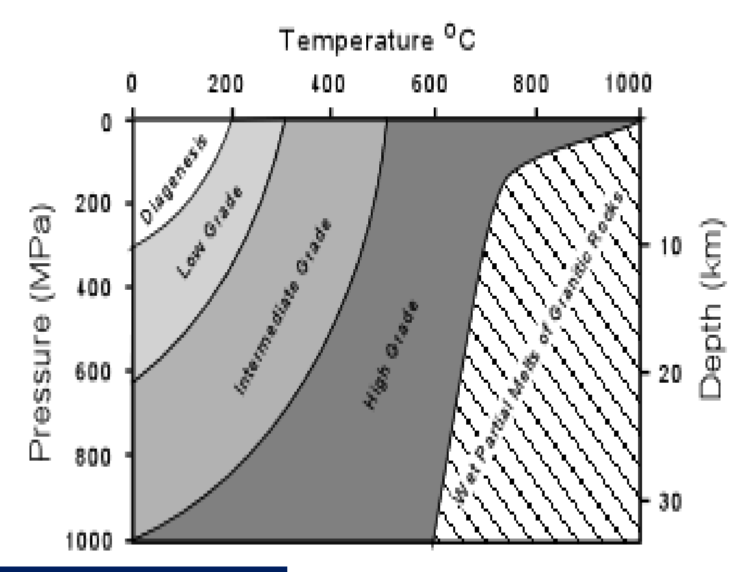


Low grade ------------------- Intermediate --------------------- High grade

Greenschist ------------- Amphibolite ---------------------- Granulite
Slate -------- Phyllite ---------- Schist ---------------------- Gneiss ----- Migmatite
Chlorite zone
Biotite zone
Garnet zone
Staurolite zone
Kyanite zone
Sillimanite zone

Grade of Metamorphism:

As the temperature and/or pressure increases on a body of rock we say the rock undergoes ***prograde metamorphism*** or that the grade of metamorphism increases. ***Metamorphic grade*** is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form.



Low-grade metamorphism takes place at temperatures between about 200 to 320°C, and relatively low pressure. Low grade metamorphic rocks are generally characterized by an abundance of hydrous minerals**.**

With increasing grade of metamorphism, the hydrous minerals begin to react with other minerals and/or break down to less hydrous minerals.

High-grade metamorphism takes place at temperatures greater than 320°C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O, and non-hydrous minerals become more common.

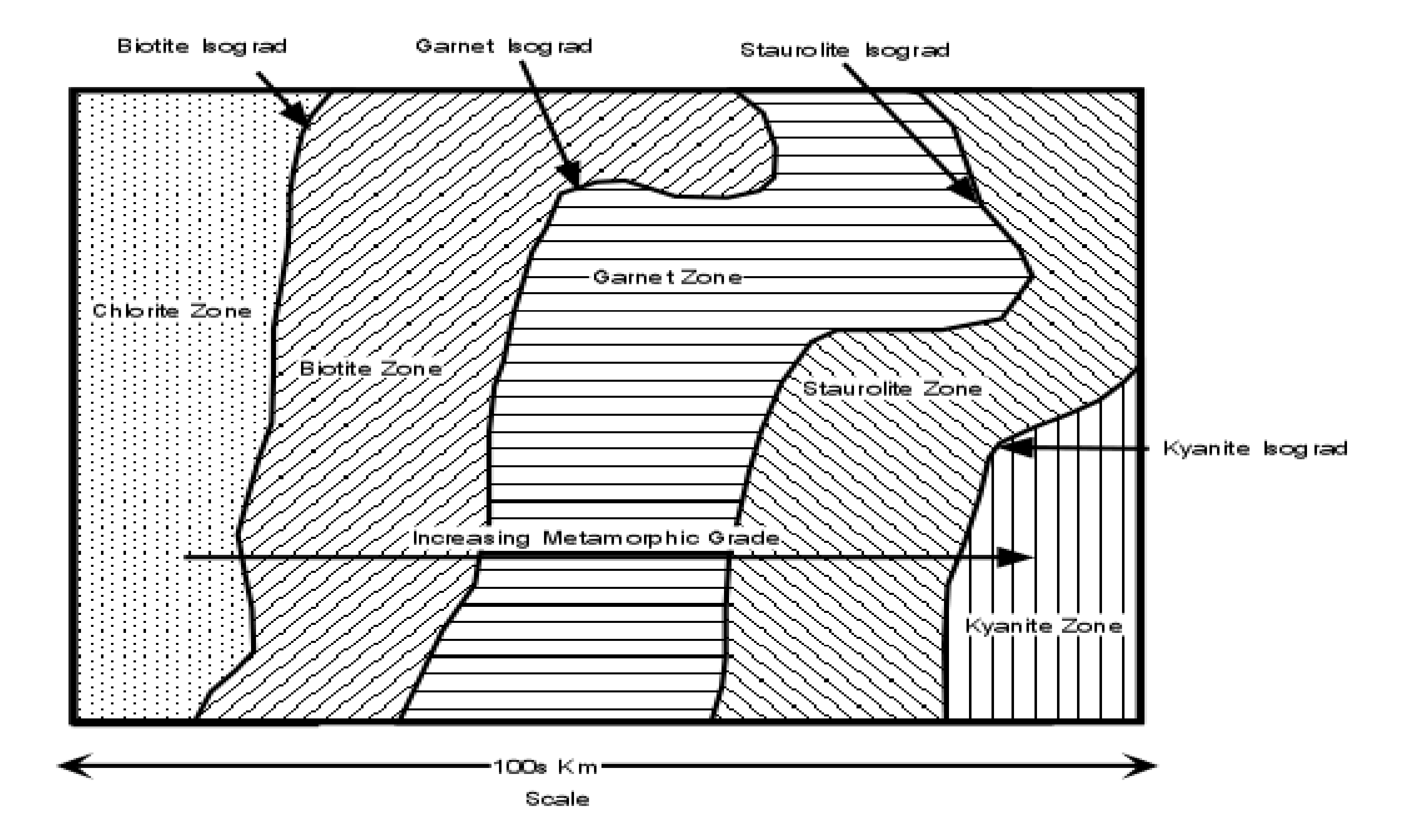
Winkler (1967) divided the entire P,T ranges of metamorphic conditions into four large large divisions of metamorphic grade. The boundaries between the four grades is marked by significant changes of mineral assemblages (specific mineral reactions):

1- Verly low-grade: diagnostic minerals are laumonite, prhenite, pumpellite, lawsonite, illite with imperfect crystallinity.

2- Low-grade: characteristic mineral assemblage is : chlorite+zoisite/clinozoisite, actinolite, quartz, chloritoid.

3- Medium-grade: appearance of cordierite, or staurolite

4- Hig grade:: breakdown of muscovite in the presence of quartz and plagioclase, formation of migmatites.



<u>Preesure divisions</u>:
1-Very-low grade: laumontite ----lawsonite----glaucophane---jadiete+quartz
2-Low-grade: almandine---glaucophane+clinozoisite
3-Medium-grade: cordierite----almandine + (Al2SiO5-polymorph)
4- High-grade:cordierite----cordierite-almandine----almandine**.**

Mineral changes in metamorphic rocks:

Changing conditions results in phase transformation from one mineral to another. Minerals coalesce or change crystal structure. The particular minerals that form are characteristic of thepressure/temperature conditions. Particularly useful for determining PT conditions are the following metamorphic index minerals

<u>Low metamorphic grade</u> (low temperatures and pressures) - about 200 degrees C Slates and phyllites are characterized by:

- **chlorite**
- **muscovite**
- **biotite**

<u>Intermediate metamorphic grade</u> rocks such as schist often have:

- **garnet**
- **staurolite**

High metamorphic grade - 800 degrees C (verging on melting), such as gneiss and migmatite have the high temperature high pressure phase sillimanite.

Staurolite, kyanite and sillimanite all have the same composition but are stable at different PT conditions (like graphite and diamond). Therefore the presence of one particular form documents the PT conditions. A more accurate idea of PT conditions can be gotten by considering a whole suite of minerals. Determining the PT history of a sequence of rocks describes the journey of that particular crustal package up and down the tectonic elevator.

Metamorphic Zones (Barrows Zones) :

change in bulk composition of the rock (Metasomatism).

In most regions of metamorphic rocks, a variation of grain size and mineralogy occurs which suggests a variation in metamorphic grade. The grain size of the rocks tends to become coarser with increasing temperature. Barrow (1912) was the first to recognize that certain newly formed minerals appear in a definite sequence with increasing temperature. These minerals were designated as index minerals. The metamorphic zones characterized by these index minerals are well developed on a regional scale in most continents.. The following succession of index minerals with increasing temperature can be distinguished in many terrains:

1-Chlorite zone: chlorite-muscovite phyllite or schist
2-Biotite zone: appearance of biotite (biotite isograde)
3-Almandine (garnet) zone: appearance of garnet.
4- Staurolite zone: appearance of staurolite
5-Kyanite zone: appearance of kyanite
6-Sillimanite zone: appearance of sillimanite and disappearance of kyanite.

An isograde is a line of outcrops on which a mineral assemblage begins to appear or disappear. Isogrades give a general picture of the P-T distribution in a metamorphic terrane.

Mineral assemblage (paragensis) : A number of different minerals in contact within a single thin section.

Types of Protolith:

1.Pelitic/mudrocks - high Al, K, Si

2. Quartzo-feldspathic - high Si, Na, K, Al

3. Calcareous- high Ca, Mg, CO_2

4. Mafic- high Ca, Mg, Fe

5. Ultramafic- very high Mg, Fe, low Si, Al

The sequence of zones now recognized, and the typical metamorphic mineral assemblage in each, are:

*__Chlorite zone__. Pelitic rocks are slates or phyllites and typically contain chlorite, muscovite, quartz and albite

* __Biotite zone__. Slates give way to phyllites and schists, with biotite, chlorite, muscovite, quartz, and albite

*__Garnet zone__. Schists with conspicuous red almandine garnet, usually with biotite, chlorite, muscovite, quartz, and albite or oligoclase

* __Staurolite zone__. Schists with staurolite, biotite, muscovite, quartz, garnet, and plagioclase. Some chlorite may persist

*__Kyanite zone__. Schists with kyanite, biotite, muscovite, quartz, plagioclase, and usually garnet and staurolite

*__Sillimanite zone__. Schists and gneisses with sillimanite, biotite, muscovite, quartz, plagioclase, garnet, and perhaps staurolite. Some kyanite may also be present (although kyanite and sillimanite are both polymorphs of Al_2SiO_5)

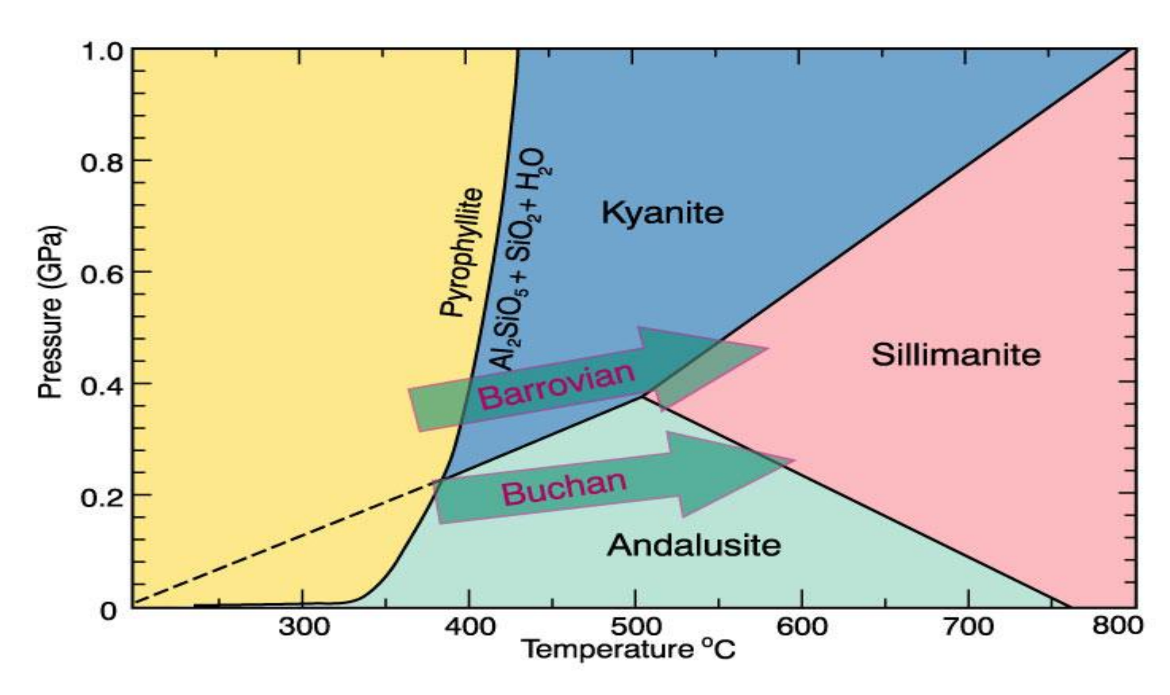
IDNEX minerals:

*Chlorite zone
*Biotite zone
*Garnet zone
*Staurolite zone
*Kyanite zone
* Sillimanite

- **Pelitic compositions are similar, but the sequence of isograds is:**

*chlorite
*biotite
*garnet
*andalusite
*sillimanite

The stability field of andalusite occurs at pressures less than 0.37 GPa (~ 10 km), while kyanite → sillimanite at the sillimanite isograd only above this pressure



. The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess silica and water. The diagram was calculated using the program TWQ (Berman, 1988, 1990, 1991).

Metamorphic Grade →

Metamorphic Facies	Greenschist	Transitional States	Amphibolite	Granulite

Albite
Plagioclase > An_{12} (Oligoclase, Andesine)
Epidote
Actinolite
Hornblende
Augite
Orthopyroxene
Chlorite
Garnet
Biotite
Quartz
Phengite
Cummingtonite

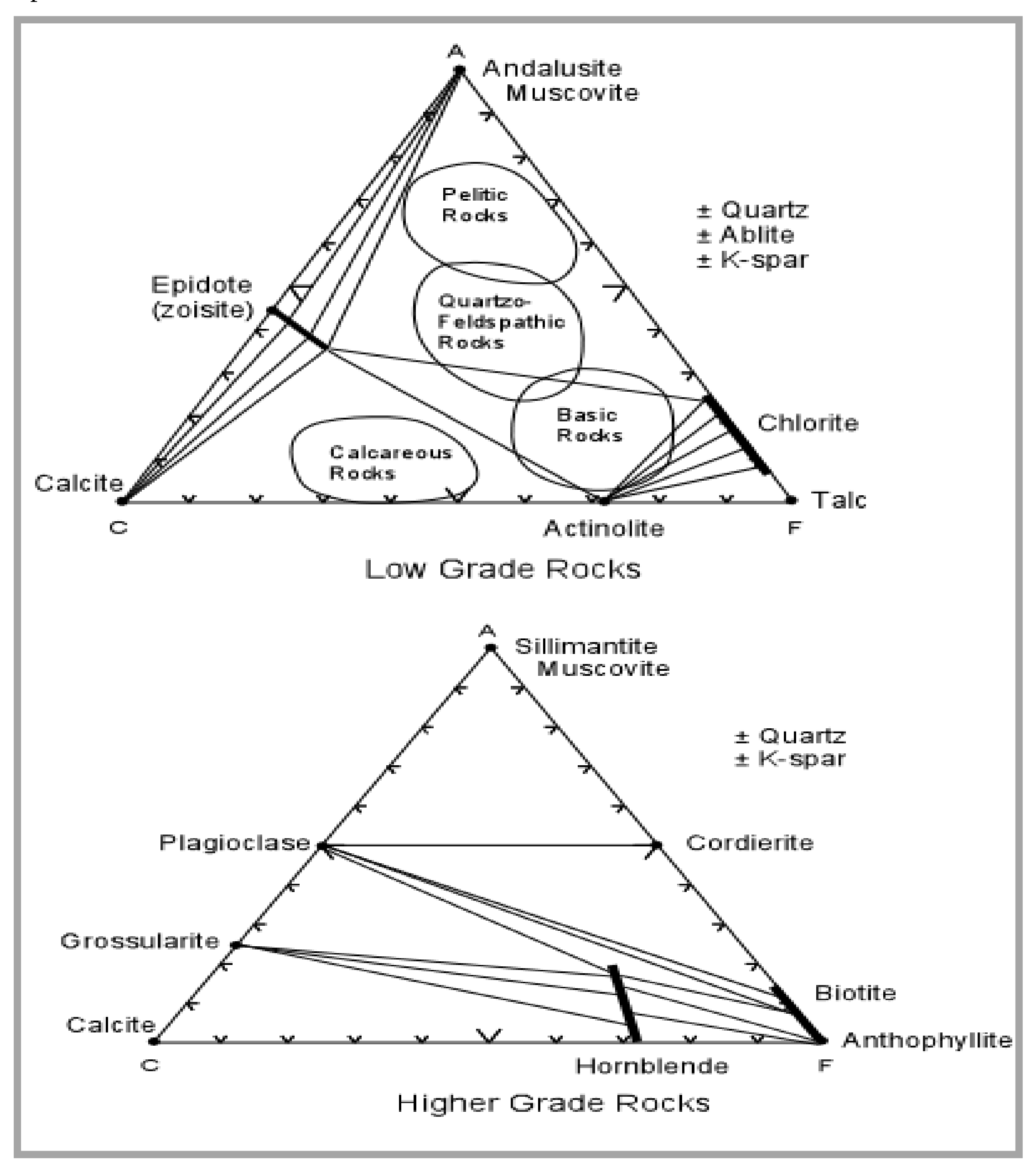
Zone for associated metapelites	Chlorite Zone	Biotite Zone	Garnet Zone	Staurolite and Kyanite Zones	Sillimanite-Muscovite Zone	K-feldspar-Sillimanite Zone	Cordierite-Garnet Zone

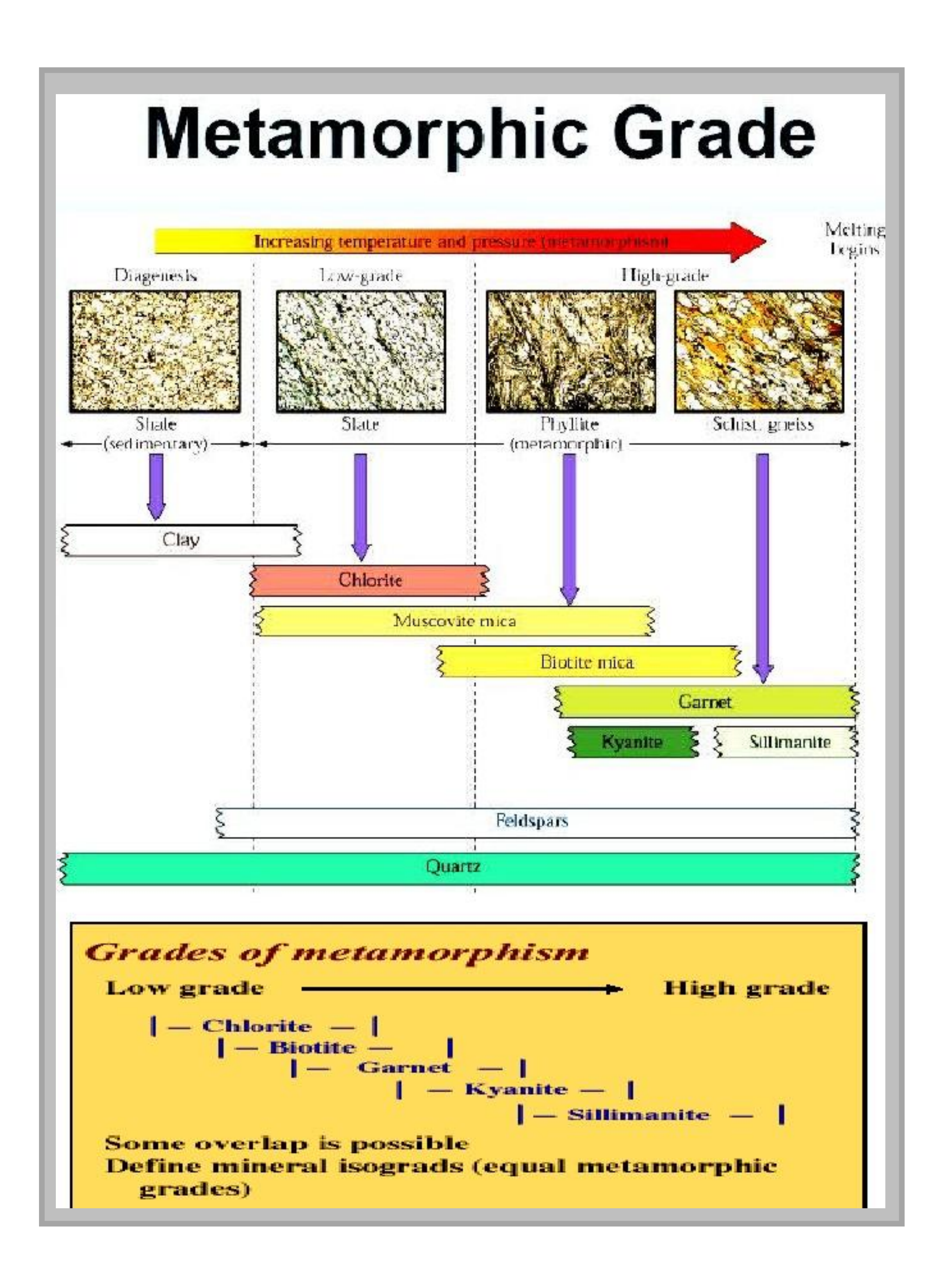
Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Prograde and retrograde metamorphism:

Metamorphism is further divided into prograde and retrograde metamorphism. Prograde metamorphism involves the change of mineral assemblages (paragenesis) with increasing temperature and (usually) pressure conditions. These are solid state dehydration reactions, and involve the loss of volatiles such as water or carbon dioxide. Prograde metamorphism results in rock characteristic of the maximum pressure and temperature experienced. Metamorphic rocks usually do not undergo further change when they are brought back to the surface.

Retrograde metamorphism involves the reconstitution of a rock via revolatisation under decreasing temperatures (and usually pressures), allowing the mineral assemblages formed in prograde metamorphism to revert to those more stable at less extreme conditions. This is a relatively uncommon process, because volatiles must be present.




Metamorphic Grade
Increasing temperature and pressure (metamorphism)
Melting begins
Diagenesis
Low-grade
High-grade
Shale
Slate
Phyllite
Schist, gneiss
(sedimentary)
(metamorphic)
Clay
Chlorite
Muscovite mica
Biotite mica
Garnet
Kyanite
Sillimanite
Feldspars
Quartz
Grades of metamorphism
Low grade
High grade
| — Chlorite — |
| — Biotite — |
| — Garnet — |
| — Kyanite — |
| — Sillimanite — |
Some overlap is possible
Define mineral isograds (equal metamorphic grades)

نطاقات العمق والتحول
Depth zones and metamorphism

ينقسم الغلاف الصخرى للأرض الى قسمين:

(أ) نطاق التجوية :Weathering zone:

وهو الجزئ العلوي من القشرة (حوالي 15 كلم) الذي يحدد بالمدي الذي يصل اليه الأكسجين والماء المتسرب ويتميز بكثرة الشقوق والمسالك وفيه تحدث عمليات الأكسدة, الكبرتة, التميؤ والذوبان.

(ب) نطاق التحول :Metamorphic zone:

وهو الجزئ السفلي من القشرة (وجزئ من الوشاح) وفيه يقل أو يندر الأكسجين والماء المتسرب وتضيق الشقوق والمسالك لتصبح تحت شعيرية ويحدث انسياب للصخر .Rock flowage

في محاولة لتحديد ظروف الضغط والحرارة المسئولة عن تكوين الصخور المتحولة في نطاق التحول (يزداد كل من درجة الحرارة والضغط مع العمق)

تم إكتشاف ثلاثة نطاقات تحول مرتبطة بازدياد العمق (,Sedeholm1891 Becke1903, Gramann1909, Niggli1924) وهى على النحو التالي:

(1) النطاق العلوى (نطاق التحول السطحى) Epi-zone:

يلي نطاق التجوية Weathering zone وتكون فيه درجات الحرارة منخفضة وكذا الضغط المنتظم لذا يكون التحول فيه نتاج الضغط الإتجاهي العالي خاصة في مناطق الفوالق والصدوع الزاحفةTransform faults كما ويساعد المحاليل المعدنية الصاعدة والهابطة في تحول الصخور.

يتميز النطاق بوجود صخور الشست الأخضر Green schist والأردواز Slate والتي تتكون من معادن السيلكات المائية مثل المسكوفايت Muscovite, الكلورايت Chlorite, التلك Talc, الأكتينولايت Actonolite, الأبيدوت Epidote والجلوكوفين Golocophane.

(2) النطاق الاوسط (نطاق التحول المتوسط) Meso-zone:

يلي النطاق العلوي وتكون فيه درجات الحرارة منخفضة نسبياً وكذا الضغط المنتظم (ولكن أعلي من النطاق السابق) ويقل الأكسجين والماء المتسرب لذا يكون التحول فيه تحولاً كيميائياً نتاج الضغط الإتجاهي.

يتميز النطاق بوجود صخور الشست schist ذات التراكيب الصفائحية Foliated والخطية Banded والغنية بمعادن المسكوفايتMuscovite, البيوتايتBiotite, الاشتارولايتStaourolite,الكيانايتKyanite, الهورنبلندHornblende, البلاجيوكليز Plagioclase والكالسايت Calcite.

(3) النطاق السفلى (نطاق التحول العميق) Hypo-zone or Kata

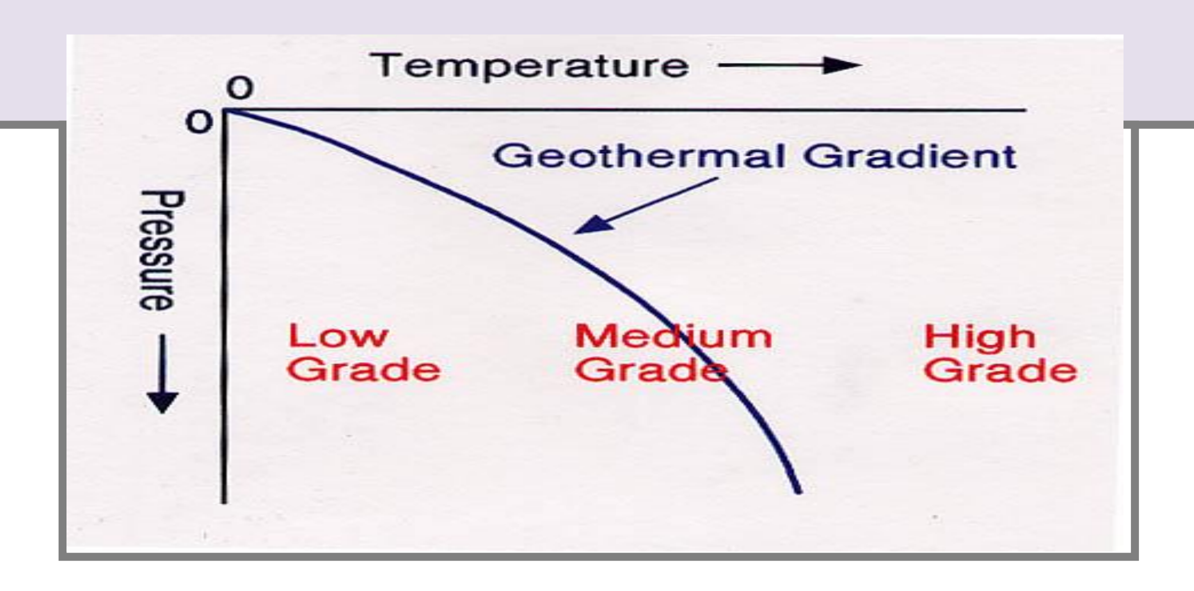
تسود فيه درجات حرارة مرتفعة جداً وكذا الضغط المنتظم غير الموجه العالي مع انخفاض شديد في الضغط الموجه ويندر الأكسجين والماء المتسرب.

يتميز النطاق بوجود صخورمتماسكة Crystalline ذات تبلور كيميائي وتشوه كبير والغنية بمعادن قريبة من المعادن المتكونة مباشرة من الصهير مثل صخور النايس Gneiss, الجرانيولايت Granulite والبيقماتايت Pegmatite والتي تحتوي غالباً علي معادن البيوتايت Biotite, الهورنبلند Hornblende, البلاجيوكليز Plagioclase, البيروكسين Pyroxeen والقارنت Garnet.

Grade of metamorphism

1- low grade – very 200 – 400 درجة
2 - low –grade
3- Medium - grade
4 - High – grade

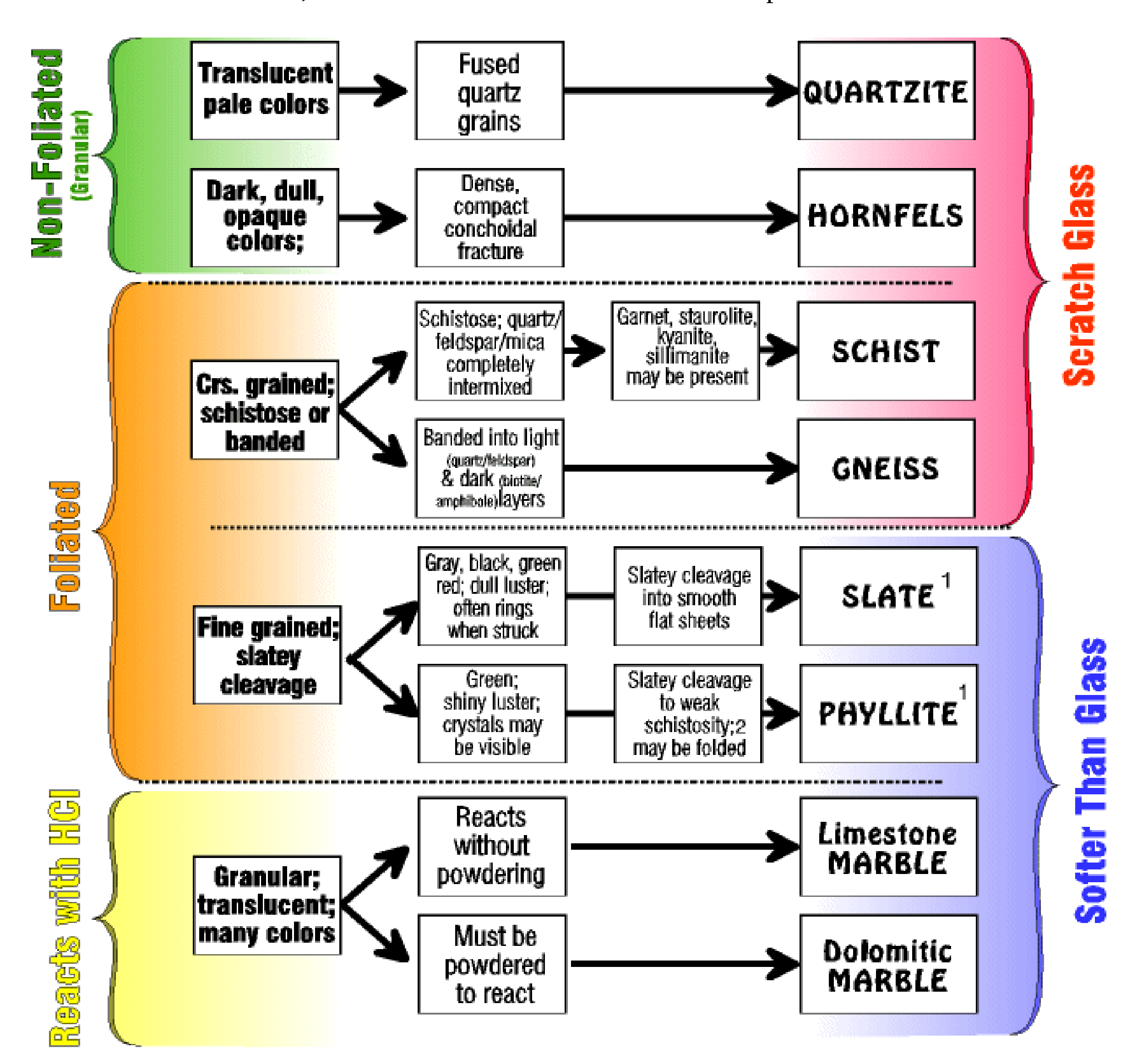
The metamorphic grade has been used as term to signify the degree of metamorphism for example low- grade metamorphism implies formation at relatively low temperatures typical of greenschist facies .



CHAPTER 3

Classification of metamorphic rocks

Classification of metamorphic rocks is based **on mineral assemblage, texture**, **protolith**, and **bulk chemical composition** of the rock. Each of these will be discussed in turn, then we will summarize how metamorphic rocks are classified.



1 (Shale), slate, and phyllite complete intergrade with each other. Distinctions may be difficult.

Classification of Metamorphic Rocks:

This Chapter is discussed in details by :

A- Textural Classification:

Two major groups of metamorphic rocks are recognized:

1- Those which are foliated (posses a definit planar structure) .

2- Those which are not foliated but are massive and structureless.

The foliated rocks may be further subdivided according to the type of foliation. A large varity of types may be subsequently be recognized in each group according to the dominant minerals.

B- Chemical and Mineralogical Classification :

1-Pelitic: Derivitives of pelitic (aluminous) sediments. Abundance of micas is characteristic.

2- Quartzfeldspathic: The principal minerals are quartz and feldspar (e.g., metamorphosed sandstones, siliceous tuffs, granites)

3- Calcareous: Derivatives of limestones , marls and dolomites.. Typicall calcite is abundant. Also characteristic are calcium and magnesium silicate such as diopside, tremolite, wollastonite and grossularite.

4- Basic : Derivative of basic igneous rocks (basalt, gabbro… et c.). Characteristic minerals are plagioclase, hornblende, Mg-chlorite, epidote.

5- Ultra-basic: Deriviativ e of peridotites. Abundance of Mg-minerals (antigorite, talc, anthophyllite, magneiste, brucite, Mg-chlorites) and absence of feldspar are characteristic.

6-Ferrugineous and manganiferous: Derviatives of cherts and other sediments containing abundant iron and /or manganese. Quartz is abundant, but feldspar is absent in typical metacherts. Magnetite, hmeatite, spessartite-almandite garnet, ferrohypersthene, stilpnomelane, Mn-epidotes and pyroxenoids are found in various combination.

Texture:

In metamorphic rocks individual minerals may or may not be bounded by crystal faces. Those that are bounded by their own crystal faces are termed ***idioblastic***. Those that show none of their own crystal faces are termed ***xenoblastic***. From examination of metamorphic rocks, it has been found that metamorphic minerals can be listed in a generalized sequence, known as the ***crystalloblastic series***, listing minerals in order of their tendency to be idioblastic. In the series, each mineral tends to develop idioblastic surfaces against any mineral that occurs lower in the series. This series is listed below:

- rutile, sphene, magnetite.
- tourmaline kyanite, staurolite, garnet, andalusite.
- epidote, zoisite, lawsonite, forsterite.
- pyroxenes, amphiboles, wollastonite.
- micas, chlorites, talc, stilpnomelane, prehnite.
- dolomite, calcite.
- scapolite, cordierite, feldspars.
- Quartz.

This series can, in a rather general way, enable us to determine the origin of a given rock. For example a rock that shows euhedral plagioclase crystals in contact with anhedral amphibole, likely had an igneous protolith, since a metamorphic rock with the same minerals would be expected to show euhedral amphibole in contact with anhedral plagioclase.

Another aspect of the crystalloblastic series is that minerals high on the list tend to form ***porphyroblasts*** (the metamorphic equivalent of phenocrysts), although K-feldspar (a mineral that occurs lower in the list) may also form porphyroblasts. Porphyroblasts are often riddled with inclusions of other minerals that were enveloped during growth of the porphyroblast. These are said to have a ***poikioblastic texture***.

Most metamorphic textures involve foliation. Foliation is generally caused by a preferred orientation of sheet silicates. If a rock has a slatey cleavage as its foliation, it is termed a ***slate***, if it has a phyllitic foliation, it is termed a ***phyllite***, if it has a shistose foliation, it is termed a ***schist***. A rock that shows a banded texture without a distinct foliation is termed a ***gneiss***. All of these could be porphyroblastic (i.e. could contain porhyroblasts).

A rock that shows no foliation is called a ***hornfels*** if the grain size is small, and a ***granulite***, if the grain size is large and individual minerals can be easily distinguished with a hand lens.

Protolith:

Protolith refers to the original rock, prior to metamorphism. In low grade metamorphic rocks, original textures are often preserved allowing one to determine the likely protolith. As the grade of metamorphism increases, original textures are replaced with metamorphic textures and other clues, such as bulk chemical composition of the rock, are used to determine the protolith.

Bulk Chemical Composition:

The mineral assemblage that develops in a metamorphic rock is dependent on

- The pressure and temperature reached during metamorphism
- The composition of any fluid phase present during metamorphism, and
- The bulk chemical composition of the rock.

Just like in igneous rocks, minerals can only form if the necessary chemical constituents are present in the rock (i.e. the concept of silica saturation and alumina saturation applies to metamorphic rocks as well). Based on the mineral assemblage present in the rock one can often estimate the approximate bulk chemical composition of the rock. Some terms that describe this general bulk chemical composition are as follows:

- ***Pelitic***. These rocks are derivatives of aluminous sedimentary rocks like shales and mudrocks. Because of their high concentrations of alumina they are recognized by an abundance of aluminous minerals, like clay minerals, micas, kyanite, sillimanite, andalusite, and garnet.

- ***Quartzo-Feldspathic.*** Rocks that originally contained mostly quartz and feldspar like granitic rocks and arkosic sandstones will also contain an abundance of quartz and feldspar as metamorphic rocks, since these minerals are stable over a wide range of temperature and pressure. Those that exhibit mostly quartz and feldspar with only minor amounts of aluminous minerals are termed quartzo-feldspathic.

- ***Calcareous.*** Calcareous rocks are calcium rich. They are usually derivatives of carbonate rocks, although they contain other minerals that result from reaction of the carbonates with associated siliceous detrital minerals that were present in the rock. At low grades of metamorphism calcareous rocks are recognized by their abundance of carbonate minerals like calcite and dolomite. With increasing grade of metamorphism these are replaced by minerals like brucite, phlogopite (Mg-rich biotite), chlorite, and tremolite. At even higher grades anhydrous minerals like diopside, forsterite, wollastonite, grossularite, and calcic plagioclase.

- ***Basic.*** Just like in igneous rocks, the general term basic refers to low silica content. Basic metamorphic rocks are generally derivatives of basic igneous rocks like basalts and gabbros. They have an abundance of Fe-Mg minerals like biotite, chlorite, and hornblende, as well as calcic minerals like plagioclase and epidote.

- ***Magnesian.*** Rocks that are rich in Mg with relatively less Fe, are termed magnesian. Such rocks would contain Mg-rich minerals like serpentine, brucite, talc, dolomite, and tremolite. In general, such rocks usually have an ultrabasic protolith, like peridotite, dunite, or pyroxenite.

- ***Ferriginous.*** Rocks that are rich in Fe with little Mg are termed ferriginous. Such rocks could be derivatives of Fe-rich cherts or ironstones. They are characterized by an abundance of Fe-rich minerals like greenalite (Fe-rich serpentine), minnesotaite (Fe-rich talc), ferroactinolite, ferrocummingtonite, hematite, and magnetite at low grades, and ferrosilite, fayalite, ferrohedenbergite, and almandine garnet at higher grades.

- ***Manganiferrous.*** Rocks that are characterized by the presence of Mn-rich minerals are termed manganiferrous. They are characterized by such minerals as Stilpnomelane and spessartine.

Classification:

Classification of metamorphic rocks depends on what is visible in the rock and its degree of metamorphism. Note that classification is generally loose and practical such that names can be adapted to describe the rock in the most satisfactory way that conveys the important characteristics. Three kinds of criteria are normally employed. These are:

1. Mineralogical - The most distinguishing minerals are used as a prefix to a textural term. Thus, a schist containing biotite, garnet, quartz, and feldspar, would be called a biotite-garnet schist. A gneiss containing hornblende, pyroxene, quartz, and feldspar would be called a hornblende-pyroxene gneiss. A schist containing porphyroblasts of K-feldspar would be called a K-spar porphyroblastic schist.

2. Chemical - If the general chemical composition can be determined from the mineral assemblage, then a chemical name can be employed. For example a schist with a lot of quartz and feldspar and some garnet and muscovite would be called a garnet-muscovite quartzo-feldspathic schist. A schist consisting mostly of talc would be called a talc-magnesian schist.

3. Protolithic - If a rock has undergone only slight metamorphism such that its original texture can still be observed then the rock is given a name based on its original name, with the prefix meta- applied. For example: metabasalt, metagraywacke, meta-andesite, metagranite.

In addition to these conventions, certain non-foliated rocks with specific chemical compositions and/or mineral assemblages are given specific names. These are as follows:

- ***Amphibolites***: These are medium to coarse grained, dark colored rocks whose principal minerals are hornblende and plagioclase. They result from metamorphism of basic igneous rocks. Foliation is highly variable, but when present the term schist can be appended to the name (i.e. amphibolite schist).

- ***Marbles***: These are rocks composed mostly of calcite, and less commonly of dolomite. They result from metamorphism of limestones and dolostones. Some foliation may be present if the marble contains micas.

- ***Eclogites***: These are medium to coarse grained consisting mostly of garnet and green clinopyroxene called omphacite, that result from high grade metamorphism of basic igneous rocks. Eclogites usually do not show foliation.

- ***Quartzites:*** Quartz arenites and chert both are composed mostly of SiO_2. Since quartz is stable over a wide range of pressures and temperatures, metamorphism of quartz arenites and cherts will result only in the recrystallization of quartz forming a hard rock with interlocking crystals of quartz. Such a rock is called a quartzite.

- ***Serpentinites:*** Serpentinites are rocks that consist mostly of serpentine. These form by hydrothermal metamorphism of ultrabasic igneous rocks.

- ***Soapstones:*** Soapstones are rocks that contain an abundance of talc, which gives the rock a greasy feel, similar to that of soap. Talc is an Mg-rich mineral, and thus soapstones from ultrabasic igneous protoliths, like peridotites, dunites, and pyroxenites, usually by hydrothermal alteration.

- ***Skarns:*** Skarns are rocks that originate from contact metamorphism of limestones or dolostones, and show evidence of having exchanged constituents with the intruding magma. Thus, skarns are generally composed of minerals like calcite and dolomite, from the original carbonate rock, but contain abundant calcium and magnesium silicate minerals like andradite, grossularite, epidote, vesuvianite, diopside, and wollastonite that form by reaction of the original carbonate minerals with silica from the magma. The chemical exchange is that takes place is called ***metasomatism.***

- ***Mylonites:*** Mylonites are cataclastic metamorphic rocks that are produced along shear zones deep in the crust. They are usually fine-grained, sometimes glassy, that are streaky or layered, with the layers and streaks having been drawn out by ductile shear.

Classification of metamorphic rocks is based on mineral assemblage, texture, protolith, and bulk chemical composition of the rock. Each of these will be discussed in turn, then we will summarize how metamorphic rocks are classified:

Contact Metamorphic Rocks:

As the name implies, these rocks are formed when one type of rock comes into contact with, or near, a source of high temperature, usually magma. This heats the parent rock to a very high temperature and creates a 'baked' zone of rock around the magma that is altered by the high temperatures to form new metamorphic rocks. This zone is called the Metamorphic Aureole and is usually relatively thin, typically between 1 and 50 meters wide.

The presence of water has an important role in creating contact metamorphic rocks. This is because the size of the aureole is partly dependent on the size of the of the

intrusive body (hence the amount of heat) and partly on the amount of water present in the surrounding rocks. In the absence of fluids, the aureole is very small.

The assemblage of new minerals that grow in the country rock depend on the original composition of the country rock. For a complex sedimentary parent of sandstones and shales, anhydrous (without water) minerals such as garnet and pyroxene occur closest to the intrusion, then hydrous (water rich) minerals such as amphibole and epidote, and at the lowest intensity, chlorite and serpentinite. When the magma comes into contact with carbonates such as limestone and dolomite the carbonate reacts with silica from the hydrothermal fluids to form Skarn. Many special lime-bearing silicate minerals form here.

Pressure has little effect on contact metamorphism because it usually takes place close to the earth's surface and also because the hot rocks become soft and can 'flow', easing the pressure away. Importantly, because the rocks are able to flow, there is rarely any internal structure or alignment and the rocks are therefore said to have a non-foliated texture. Examples of contact metamorphic rocks are hornfels, quartzite and marble.

Regional Metamorphic Rocks :

These rocks form where pressure is the dominant transforming agent. It is important to note that heat may not be entirely absent, but it is the pressure which determines how the rocks are altered in this case. This type of metamorphism usually takes place deep underground, hence the high pressure, and is usually associated with mountain-building processes.

Although the pressure is applied from all sides, the fact that the crust is undergoing dynamic changes means that the pressure is not always equal from all directions. This causes stresses called Differential Stress. The result is to frequently deform the rocks into stretched or flattened forms. The stress also creates shearing, causing different parts of the rock to move against each other in a plane. When minerals align themselves in this way it is **called Foliation** and such rocks are said to have a foliated texture. Geologists have identified three different types of foliated rocks and these are commonly used to classify regional metamorphic rocks into three generic groups:

- Rocks that split easily along a flat/parallel plane; composed of microscopic platy minerals. The generic rock name for rocks with this texture is Slate.
- Rocks that have visible platy minerals (like mica) growing parallel to a plane created by differential stress. This is said to have a schistose texture and the rock with this type of texture is called Schist.
- When a metamorphic rock becomes very plastic due to heat and pressure, the minerals are often divided into distinct light and dark layers which are said to have a gneissic texture. The rock with this type of texture is called Gneiss.

The classification of metamorphic rocks therefore largely depends on their texture and structural features. One of the first things geologists look for is whether the rock is foliated or not. This immediately determines whether it is a contact or regional metamorphic rock. If the rock is foliated they will look at the alignment of the texture and after that at the mineral content. This is usually enough to name the majority of metamorphic rocks.

However, more recently, the classification of Regional Metamorphic Rocks has been refined further. This uses the idea of a Geothermal Gradient which takes more account of heat involved in rock formation and not just pressure. Consequently there is some overlap with Contact Metamorphism. Nevertheless, still keeping the Contact Metamorphic group largely separate, according to this scheme.

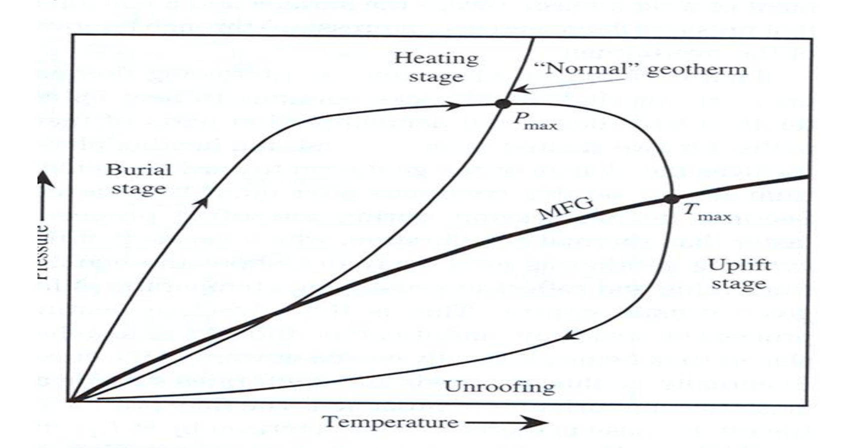
Regional Metamorphism :

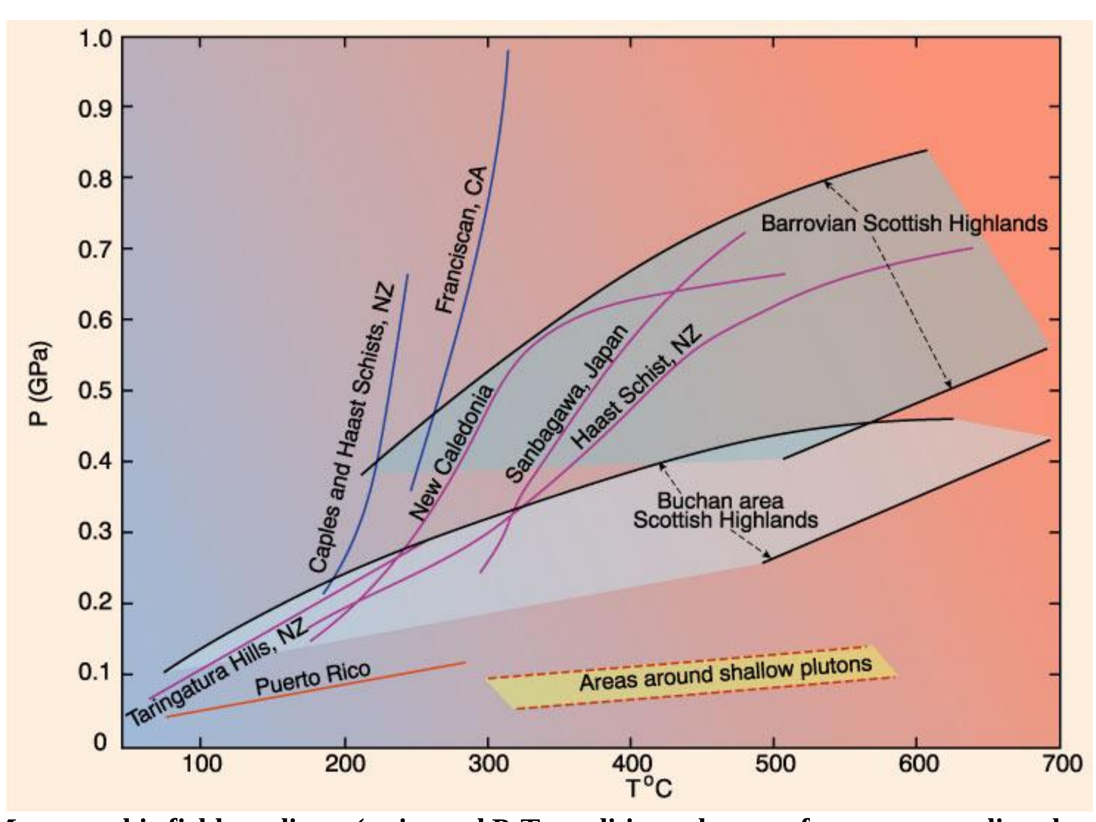
3 stages:

1-Burial/crustal thickening.

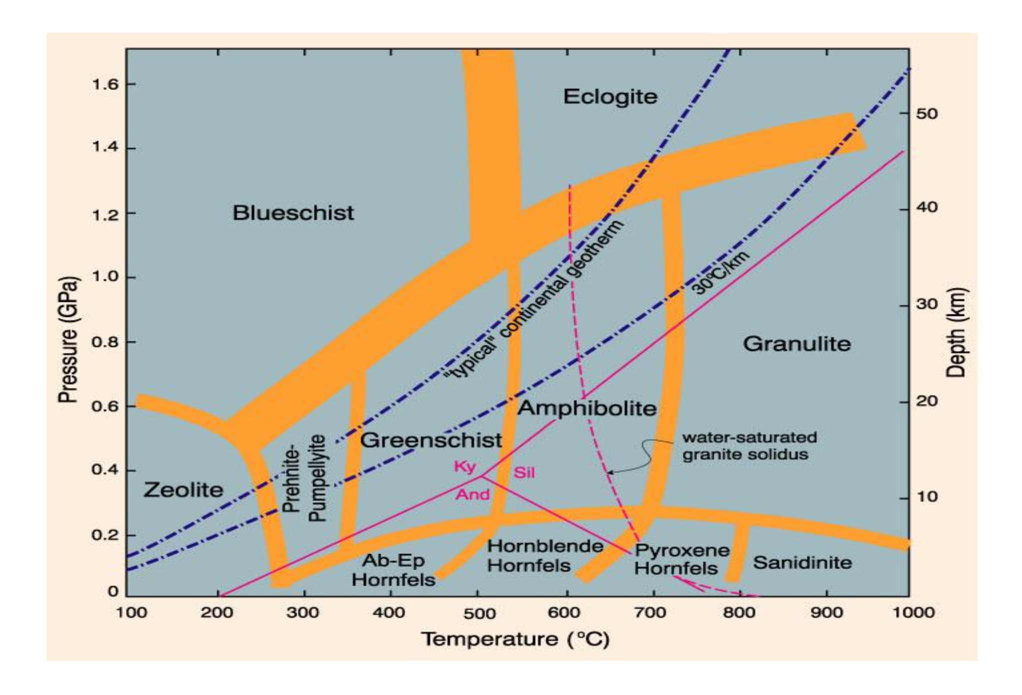
2-Heating stage.

Uplift stage .





Metamorphic field gradients (estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981). ***Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*****. McGraw-Hill.**



Regional Metamorphic Rocks can be subdivided into:

Barrovian Metamorphism - this takes place in regions of mid-temperature and mid-pressure. They represent the most common, widespread, large scale metamorphism typically associated with major orogenic (mountain building) events. The parent rock is usually sedimentary and transforms along a defined sequence according to rising temperature and pressure:

Sedimentary Rock > Shale > Slate > Phyllite > Schist > Gneiss

If the starting material is igneous rock, such as basalt, the sequence is defined as:

Basalt > Green-Schist > Ambibolite >> Granulite

Importantly, each step along the igneous sequence is associated with the formation of specific minerals. Thus the Green-Schist zone leads to the formation of Chlorite, Muscovite and Biotite. The Ambibolite zone leads to the formation of Garnets, Staurolite and Kyanite. Finally, the Granulite zone leads to the formation of Sillimanite. The identification of each of these minerals in a sample can therefore give a measure of the metamorphic intensity.

Blue-Schist Metamorphism - this takes place in regions of low temperature and high pressure. Blueschist metamorphism occurs at convergent plate boundaries in subduction zones, either under volcanic arcs, or under continents (cordilleran type). Here cold oceanic crust and sediment is rapidly subducted. Pressure increases quickly because of depth, but the temperature lags behind because the rock is being buried faster than it can heat up. Rocks appear blue from amphibole mineral Glaucophane.

Eclogite Metamorphism - this takes place in regions of moderate temperature and very high pressure.Eclogite metamorphism takes place in or near the Mantle. The parent rock is ultramafic mantle material, such as peridotite. Eclogite is characterized by a pale green sodic pyroxene (omphacite) and a red garnet (almandine-pyrope), making it a striking rock. Associated minerals are Rutile, Kyanite, and Quartz, and it is not unusual to have retrograde amphibole in the rock too. Since eclogite forms so deep, surface outcrops are not common.

Further to adding more detail to Regional Metamorphism, the concept of the Geothermal Gradient also includes the activity of Hydrothermal Metamorphism. This takes place in near-surface regions of low temperature and low pressure where large amounts of water are present. Hydrothermal metamorphism occurs when warm, chemically active, mineral-laden waters interact with the surrounding rock. It is one of the most common and widespread types of metamorphism, although most of it

cannot be seen easily. There are also several distinctly differnt types of hydrothermal metamorphism:

- **Igneous Fluids and Pegmatites**: The most spectacular hydrothermal metamorphism takes place as an after effect of igneous activity. Magmas have lots of water with dissolved minerals, but as the magma crystallizes the mineral laden water is driven off into the surrounding country rock where it seeps into cracks and pores precipitating the minerals. The most important result of this is a pegmatite, a very coarse grained felsic igneous rock. Pegmatites commonly have single crystals measured in meters in size, as well as a host of exotic minerals, including some of the most important gem minerals. Hydrothermal deposits of this type also produce many important mineral deposits, including the ores of lead, copper, silver and gold.

- **Oceanic Hydrothermal Metamorphism**: A second type of hydrothermal metamorphism takes place at oceanic rift centers (divergent plate boundaries). Here magma oozes out onto the ocean floor to form pillow basalts. While the rock is still hot sea water carrying all its salts percolates into the rocks where a lot of chemical reactions take place. Minerals are leached out of the rock and carried to the surface where they often form smokers and gysers on the ocean floor.

Metamorphic processes:

Recrystallization:

During recrystallization, the grains making up the protolith change shape and size. The identity of the mineral does not change during this process, only the texture. Recrystallization occurs due to heating of the protolith. The temperature at which this occurs can vary depending on the minerals present. Recrystallization generally begins when temperatures reach above half the melting point of the mineral on the Kelvin scale.

Phase change:

Phase change metamorphism is the creating of new minerals with the same chemical formula as the protolith. This involves a rearrangement of the atoms in the crystals.

Neocrystallization:

Neocrystallization involves the creation of new mineral crystals different from the protolith. Chemical reactions digest the minerals of the protolith which yields new minerals. This is a very slow process as it can also involve the diffusion of atoms through solid crystals.



Pressure solution:

Pressure solution is a metamorphic process that requires a rock to be under strong pressure from one direction and in the presence of hot water. During this process mineral of the protolith partially dissolve, diffuse through the water and precipitate elsewhere

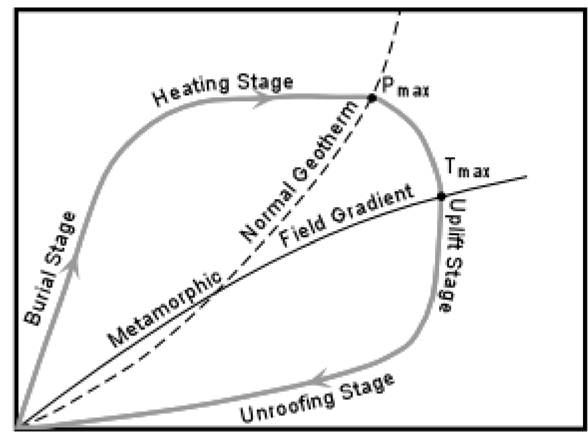
Plastic deformation:

In plastic deformation pressure is applied to the protolith, which causes it to shear or bend, but not break. In order for this to happen temperatures must be high enough that brittle fractures do not occur, but not so high that diffusion of crystals.

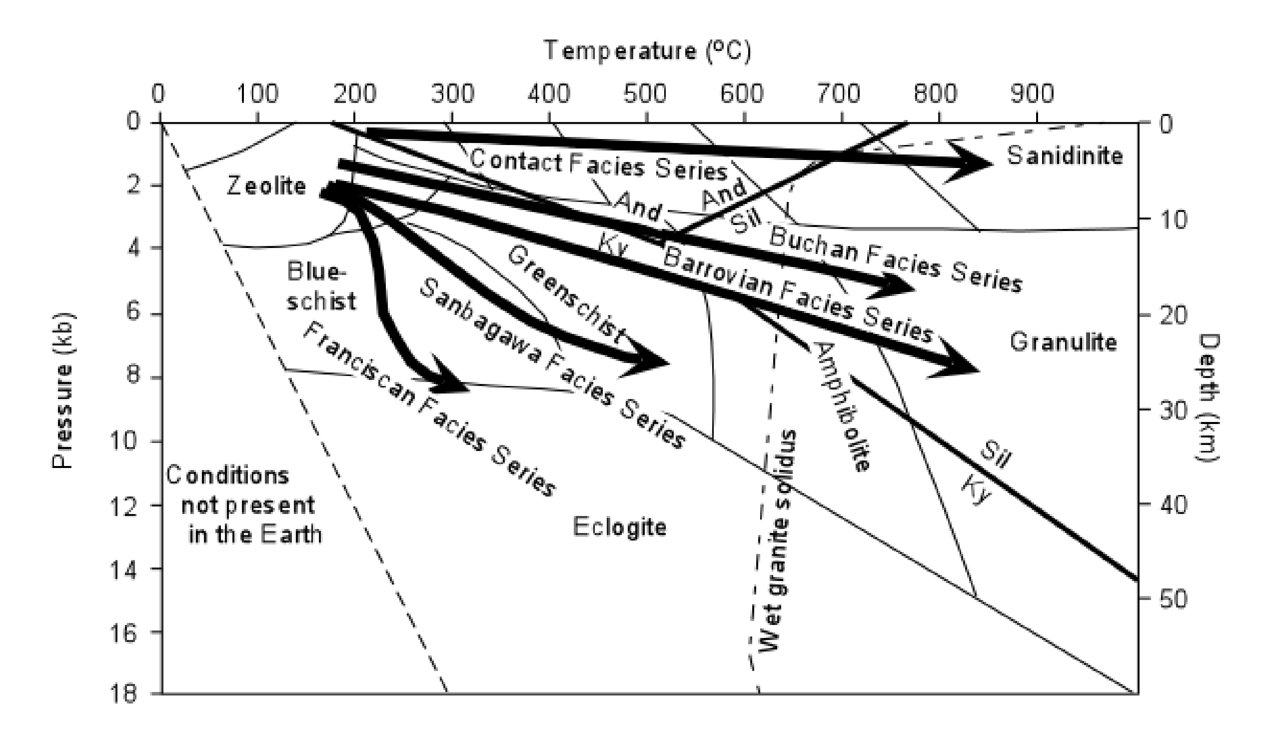
Metamorphic Field Gradients:

As rocks are pushed deeper into the Earth as a result of tectonism, they will encounter four stages during which temperature and pressure change in the rock in different ways.

- During the burial stage the effects of increasing pressure are encountered by the rock immediately as depth of burial increases. But increasing temperature will take time, because heat has to be conducted into the rock in order to increase the temperature to that of the surroundings. So, the rock will follow a path resembling a low geothermal gradient.



- When the rocks are nearly buried to their maximum depth, heat conducted from below will cause an increase in temperature and the rock will undergo a heating stage at a pressure equivalent to the maximum pressure encountered by the rock. Along this path the rock will encounter the temperature and pressure of the regional geothermal gradient and will also encounter the maximum pressure of metamorphism.
- As rocks heat up, they will decrease in density, and thus there will be an isostatic response to the heating, wherein the rocks will begin to rise resulting in uplift of the overlying rock. Uplift alone will not cause a decrease in pressure, but erosion of the uplifted region will remove material and eventually pressure will start to decrease. During this uplift stage, the rocks will continue to gain temperature because they are expanding and they are carrying heat with them. At some point during this uplift stage, the maximum temperature will be encountered.
- The unroofing stage occurs when erosion rates become high enough that pressure starts to decrease. As rocks move to a lower pressure environment heat will conducted into their surroundings and temperature will decrease to that present on the surface.



Since chemical equilibrium will be controlled more by temperature than by pressure, the mineral assemblages will reflect those stable at the maximum temperature, but not necessarily the maximum pressure. Thus, the geothermal gradient deduced from a series of rocks in any area will reflect a thermal gradient somewhat higher than the true geothermal gradient. To distinguish between the true geothermal gradient and that deduced from the facies series, the deduced geothermal gradient is called the ***metamorphic field gradient***.

يصعب وضع تصنيف مثالي مناسب للصخور المتحولة وذلك لأن المادة الأولية الواحدة يمكن ان تعطي أنواع مختلفة تماماً من الصخور تبعاً لاختلاف أنواع التحول وكذلك الصخور المتحولة المتشابهة تماماً يمكن ان تكون نتاج مواد أولية مختلفة.

هنالك عدة محاولات لتصنيف الصخور المتحولة أهمها:

(أ) تقسيم الصخور المتحولة تبعاً للتركيب الكيميائى لأصل المكونات :

قسمت الصخور المتحولة الى ست مجموعات على أساس اصل مكوناتها على النحو التالى:

1- الصخور المتحولة المشتقة من الصخور الطينية(الطين الصفحي والصلصال) وهذه تسمي Pelitic sediments وتكون دائماً غنية بسليكات الألومونيوم المائية وأكاسيد البوتاسيوم (K2O).

2- الصخور المتحولة المشتقة من الصخور الرملية أو الصخور الغنية بالكوارتز والفلسبار (مثل الصخور النارية الحمضية) وهذه تسمي Psammitic sediments او Quartz-feldspathic sediments وتكون دائماً غنية بسليكات الصوديوم وفقيرة بأكاسيد CaO, FeO, MgO وتحتوي علي معادن البلاجيوكليز.

3- الصخور المتحولة المشتقة من الصخور الجيرية (الحجر الجيري والدولومايت) وهذه تسمي Calcareous sediments وهي في معظمها صخور الرخام الغنية بالكالسايت والدولومايت.

4- الصخور المتحولة المشتقة من الصخور النارية القاعدية (الجابرو والبازلت) وهذه تسميBasic rocks وهي في معظمها صخور تحتوي علي الهورنبليد, البيروكسين والبلاجيوكليز الكلسي.

5- الصخور المتحولة المشتقة من الصخور الماغنيسية (الدونايت-البريدوتايت) وهذه تسمي Ultabasic rocks وهي في معظمها صخور غنية بالأولفين, البيروكسين والبلاجيوكليز الكلسي.

6- الصخور المتحولة المشتقة من الصخور الحديدية المانجنيزية (صخور رسوبية حديدية) وهذه تسميFerruginous rocks وهي في معظمها صخور تحتوي علي معادن الماجنيتايت, الهيماتايت والجارنت.

(ب) تقسيم الصخور المتحولة على حسب البنيات:

من التصانيف الحديثة والمستخدمة بكثرة وهو تصنيف علي أساس البنيات والأنسجة الرئيسية للصخور المتحولة ومعادنها.

يمكن تصنيف الصخور المتحولة علي هذا الأساس الي مجموعتين:

الصخور المتورقة (الصفائحية) Foliated rocks:

وهي الصخور التي تتكون من بلورات معدنية قشرية Flaky, أنبوبية Tabular, او إبريةNeedle-like الشكل, ويتم تنظيم هذه البلورات بحيث تكون محاورها الطويلة متورازية فتكوّن بنية طبقية Layered, صفائحيةLaminated او حزميةBanded.

الصخورغيرالمتورقة (غير الصفائحية) Non-foliated rocks:

وهي الصخور التي تتميز بالنسيج الكتلي الكثيفMassive او الحبيبىGranular.

CHAPTER 4

Types of Metamorphic Reactions

Chemical reactions that take place during metamorphism produce mineral assemblages stable under the new conditions of temperature and pressure. Thus, in order to understand the mineral assemblages and what they mean in terms of the pressure and temperature of metamorphism, we must first explore the various types of metamorphic reactions. A metamorphic reaction is an expression of how the minerals got to their final state, but a reaction does not necessarily tell us the path that was actually taken to arrive at this state. Sometimes it is possible to deduce the path by means of a reaction mechanism. Thus, we will also explore reaction mechanisms.

If we are considering a rock of fixed chemical composition, then a metamorphic reaction states the principles of equilibrium. In other words, if we can write a reaction expressing equilibrium between the minerals we see in the rock, we expect that the reaction must have been taking place during metamorphism. We will first look at various types of metamorphic reactions.

Type of metamorphic reactions:

Polymorphic phase transformation:

The simplest metamorphic reaction involves polymorphic transformation of minerals as *P* or *T* changes. The most important metamorphic polymorphs are in the Al_2SiO_5 system, the minerals *andalusite*, *kyanite*, and *sillimanite*. The transformation of calcite to aragonite with pressure in subduction zones is also an important metamorphic transformation.

Solid-solid net-transfer reactions:

These reactions involve the formation of a new mineral assemblage from an old mineral assemblage, without the involvement of a volatile phase. An example is the reaction:

$$\mathbf{NaAlSi_3O_8\ (albite) \rightarrow NaAlSi_2O_6\ \ (jadeite) + SiO_2\ (quartz),}$$

that occurs in subduction zones with increase in pressure.

Another example is the reaction

$$\mathbf{Mg_3Si_4O_{10}(OH)_2\ (talc) + 4\ MgSiO_3\ (enstatite) \rightarrow Mg_7Si_8O_{22}(OH)_2\ \ (anthophyllite)}$$

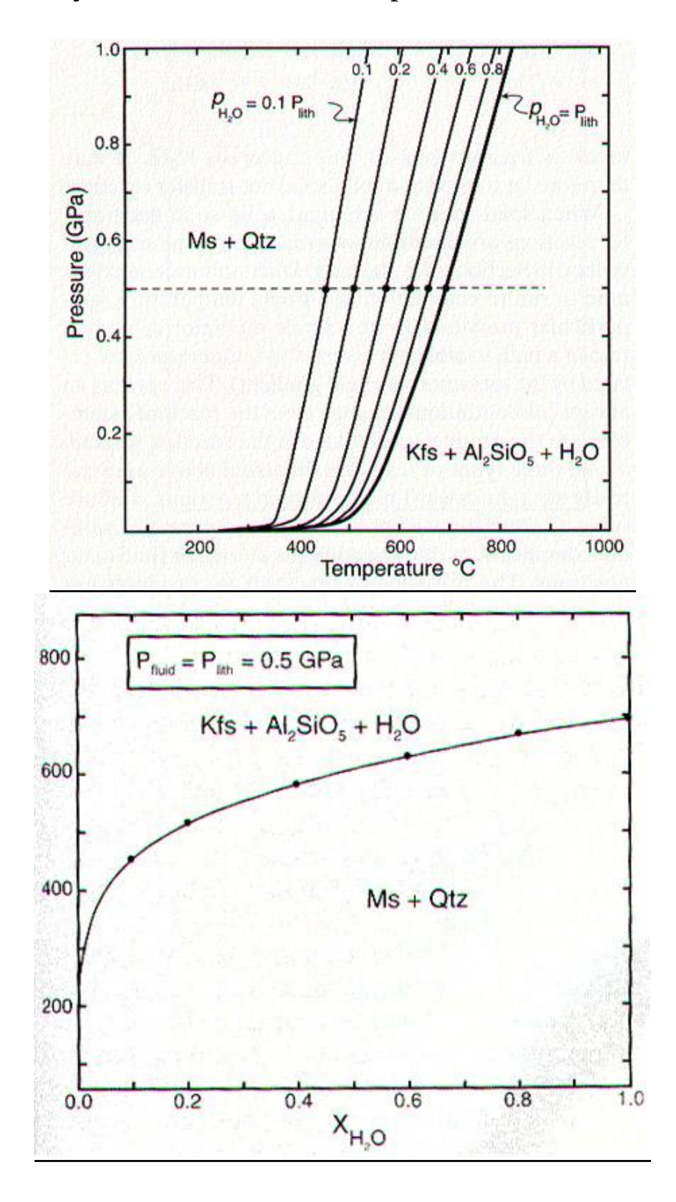
This reaction has hydrous minerals, but no volatile phase is produced or consumed.

Devolatilization reactions:

Most metamorphic reaction involve the production or consumption of a volatile phase. Because they also involve a change in modal proportion of minerals, they are also net-transfer reactions. An example is:

$$KAl_2AlSi_3O_{10}(OH)_2 + SiO_2 \rightarrow KAlSi_3O_8 + Al_2SiO_5 + H_2O \; .$$

Because devolatilization reactions involve production of a high-volume volatile phase (the reactions have high positive ΔV), the temperatures that these reactions occur at are highly dependent on pressure and the proportion of the relevant volatile component in the fluid phase, because the fluid phase may contain additional component, such as CO_2.

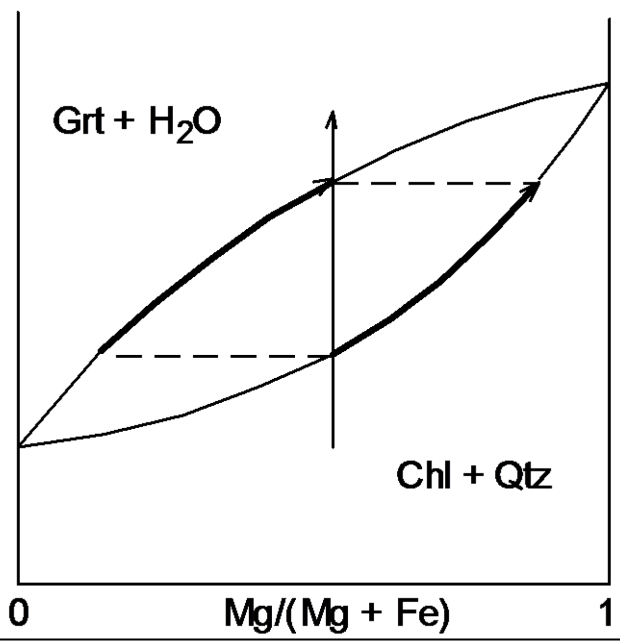


Continuous reactions:

Rocks that contain minerals that are solid solutions usually undergo *continuous* reactions over a broad temperature range. Continuous reactions are particularly important in pelitic rocks in that minerals have variable Fe/Mg ratios. Consider the reaction

Chl + Qtz → Grt + H_2O .

Chlorite, garnet and biotite are all solid solutions containing Fe and Mg end-members. This implies that the reaction will occur over a given temperature range, depending on the Fe/Mg ratio of the rock. This reaction can be illustrated using the following schematic phase diagram, that looks just like the olivine-melt or plagioclase-melt binary diagrams that we covered in igneous petrology:



During the reaction, the first garnet that will form will be more Fe-rich than chlorite. With increasing *T*, more garnet will form at the expense of chlorite as both will become more Mg-rich. The reaction will be completed when all chlorite disappears.

Ion-exchange reactions:

Ion-exchange reactions involve the exchange of two ions between two minerals as a function of temperature and/or pressure. An ion-exchange may or may not involve a continuous reaction as above. An example of an ion-exchange reaction in which no mineral is consumed or produced is the Fe-Mg exchange between biotite and garnet. The exchange reaction is written in the following forms:

annite + pyrope = phlogopite + almandine

or

$$X_{Fe}^{bt} + X_{Mg}^{grt} = X_{Mg}^{bt} + X_{Fe}^{grt}$$

Ion-exchange reactions form the basis for geothermometry and geobarometry to be covered later.

Oxidation/reduction (redox) reactions:

These reaction involve the addition or removal of oxygen from the rocks. They primarily involve oxide minerals. Two examples are:

$$4\ Fe_3O_4 + O_2 \rightarrow 6\ Fe_2O_3 \quad (MH)$$

or

$$3\ Fe_2SiO_4 + O_2 \rightarrow 2\ Fe_3O_4 + 3\ SiO_2 \quad (FMQ)$$

(These reactions also occur in igneous rocks). At a given pressure, these reactions are univariant. Therefore, when minerals on both sides of the reaction are present, at a given temperature they fix (buffer) the partial pressure of oxygen (*fugacity*) in the rock or magma.

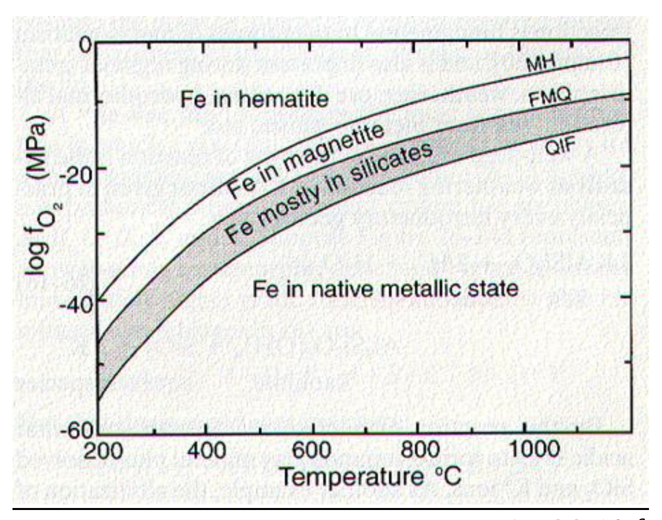


Fig. 26-10 from Winter, 2001

Metasomatic ion-exchange reactions:

These reactions involve the exchange of ions between fluids and minerals. Therefore these reactions can be thought of as *diagenetic* reactions. Some examples include:

$$NaAlSi_3O_8 + K^+Cl^- \text{ (in fluid)} \rightarrow KAlSi_3O_8 + Na^+Cl^- \text{ (in fluid)} \quad \text{[occurs at high } T\text{]}$$

or

$$2\ KAlSi_3O_8 + 2\ H^+ \text{ (acid)} + H_2O \rightarrow Al_2Si_2O_5(OH)_4 \text{ (kaolinite)} + SiO_2 + 2\ K^+ \quad \text{[true diagenesis].}$$



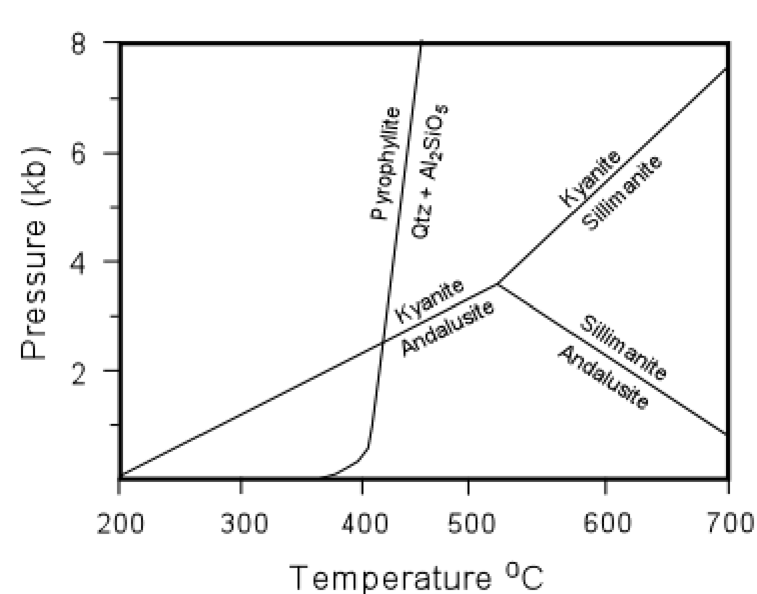
Univariant Reactions:

For a given rock composition, a univariant reaction is one that plots as a line or curve on a pressure-temperature diagram. If all phases in the reaction are present in the rock, then we know that the rock must have been metamorphosed at some pressure and temperature along the reaction boundary Consider for example the simple Al_2SiO_5 system with excess SiO_2 and H_2O. In low grade metamorphic in this system, the reaction:

$Al_2Si_4O_{10}(OH)_2 \Leftrightarrow Al_2SiO_5 + 3SiO_2 + H_2O$

Pyrophyllite Ky or Andal Qtz fluid

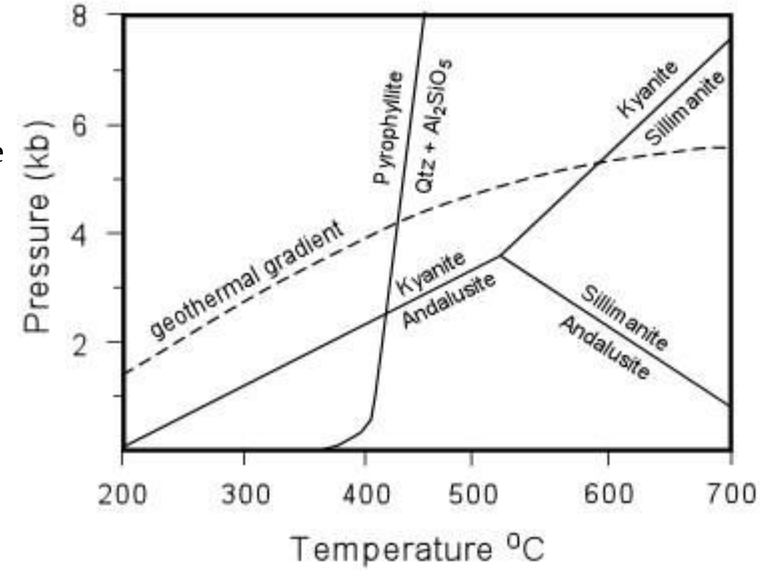
defines a reaction boundary on a P-T diagram. This boundary can be determined experimentally or can be calculated using thermodynamic properties of the phases involved. If we find a rock that contains pyrophyllite, quartz, and an Al_2SiO_5 mineral, then we know that metamorphism took place somewhere along the trajectory of the reaction boundary. Furthermore, combining this with the knowledge of the stability fields of the Al_2SiO_5 minerals, we could place boundaries on the conditions of metamorphism.

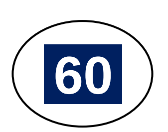


For example, if the mineral is andalusite, then we know the rock was metamorphosed at a pressure less than about 2.5 kilobars. If the mineral is kyanite, then we know that the pressure was greater than about 2.5 kilobars.

Combinations of other such reactions could further constrain the pressure and temperature conditions of metamorphism. The example above, however, is probably too simple for a real rock.

Although simple, we can use the diagram to illustrate another point. Imagine that a group of rocks are buried along the geothermal gradient shown in the diagram to the right. Rocks buried to a pressure less than about 4 kb and a temperature less than about 420 °C should have pyrophyllite so long as they have the right composition. Rocks buried to pressures between about 4 and 5 kb and temperatures between 420 and about 600 °C should have kyanite + quartz, and rocks buried to pressures along the geothermal gradient greater than

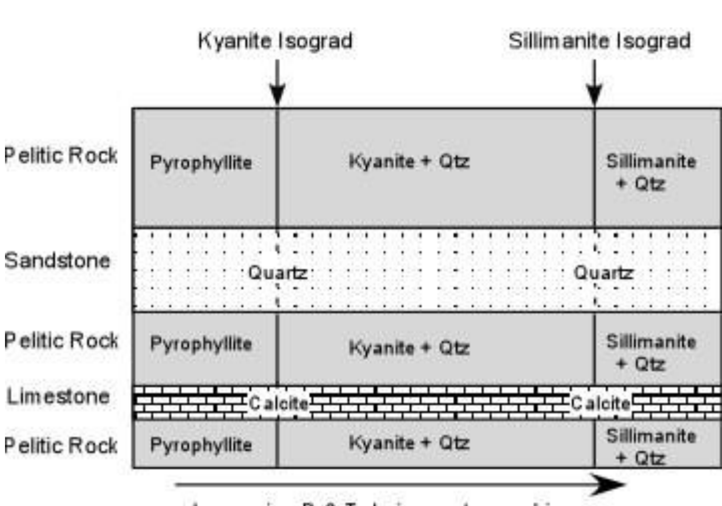




about 5 kb and temperatures greater than about 600 °C should have Sillimanite + Quartz.

Now imagine that these rocks are brought back to the surface of the Earth and that retrograde metamorphism did not occur on the reverse path back to the surface. Furthermore, they are fortuitously exposed so that the strike direction of the rocks is coincident with the direction along which temperature and pressure increased along the geothermal gradient during the metamorphic event.

If we walk along the outcrop along the strike direction (coincident with the direction that pressure and temperature increased during metamorphism) we see that in pelitic rocks the low P & T end of the outcrop has a mineral assemblage consisting of only pyrophyllite. Walking further along strike, we suddenly come to a place where the mineral assemblage changes to Kyanite + Quartz. Note that if were making a geologic map, we could draw a line on the map that separates the pelitic rocks containing only Pyrophyllite from those containing Kyanite + Quartz. Such a line (a surface in 3 dimensions) is called an isograd (iso - same, grad - grade).



In this case, since it represents the first appearance of Kyanite, we call it the Kyanite Isograd.

Notice that the isograd represents the point on the phase diagram, above where the geothermal gradient intersects the boundary for the reaction:

$$Al_2Si_4O_{10}(OH)_2 \Leftrightarrow Al_2SiO_5 + 3SiO_2 + H_2O$$

Pyrophyllite **Kyanite** **Qtz** **fluid**

Also notice that if were were walking along an outcrop of the sandstone or the limestone, that we would not be able to map this isograd in these rocks. The reason of course is that the sandstone, made of pure grains of quartz, and the limestone, made of pure grains of calcite, do not have the necessary chemical constituents to form minerals like Pyrophyllite and Kyanite.

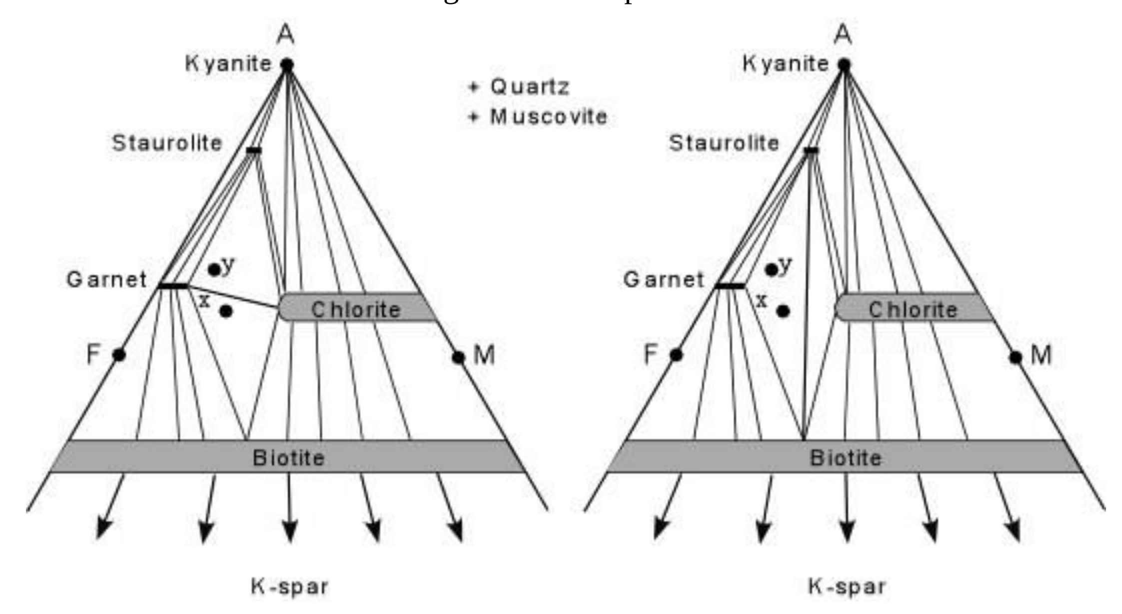
If we continue walking along the direction that T & P increased in these rocks during metamorphism, we would eventually come to another place where in the pelitic rocks the mineral assemblage changes. This time the change is from Kyanite + Quartz to Sillimanite + Quartz. Again, we can draw a line on the map that indicates this change in mineral assemblage, this time calling it the Sillimanite Isograd. Just like before, this represents the point on the phase diagram, above, where the geothermal gradient intersected the boundary for the reaction:

Al_2SiO_5 <=> Al_2SiO_5

Kyanite Sillimanite

Because the sandstone and the limestone do not contain Kyanite, the isograd does not appear in these rocks, but we can still extrapolate its position across the map or outcrop.

On mineral compatibility diagrams, univariant reactions may show up as flipping tie lines. To illustrate this we will use the AFM diagram for metapelites.



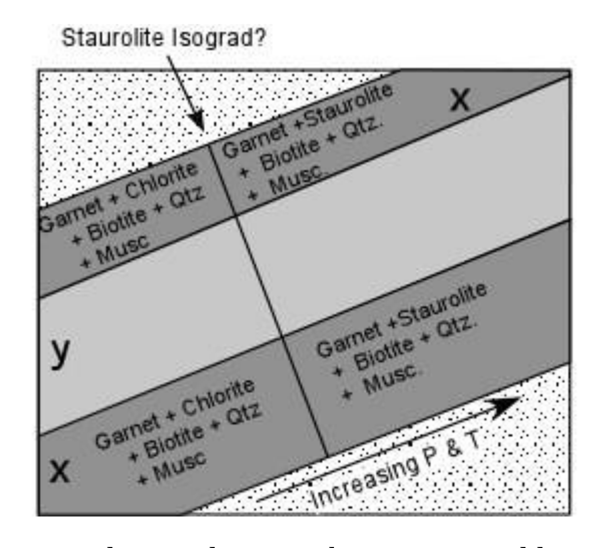
In the diagrams, the average pelitic rock is shown as composition x. At low grade, the stable mineral assemblage is Garnet + Chlorite + Biotite + Muscovite + Quartz. As temperature and pressure are raised, this assemblage becomes unstable and the tie line connecting Garnet and Chlorite is replaced by one connecting Staurolite + Biotite.

The reaction that occurred is the univariant reaction:

Garnet + Chlorite + Muscovite = Staurolite + Biotite + Quartz + H_2O

Imagine now that we are looking at a suite of metamorphic rocks in the field that include a pelitic rocks of composition x.

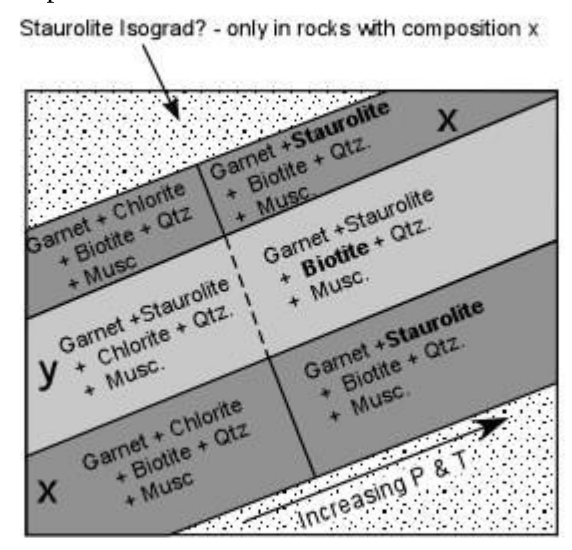
As we follow an outcrop of this rock we note that it contains the mineral assemblage Garnet + Chlorite + Muscovite + Quartz. We eventually reach a point in the outcrop where the mineral assemblage abruptly changes. Chlorite is no longer present, but instead we find Staurolite. We can now place a line on our map that represents the first appearance of staurolite in these rocks and that point represents a point on what we might call the Staurolite isograd. We would then know that the pressure and temperature conditions must have reached the reaction boundary where the reaction listed above took place.



This isograd, however, would probably not be a very good isograd to map, because it would

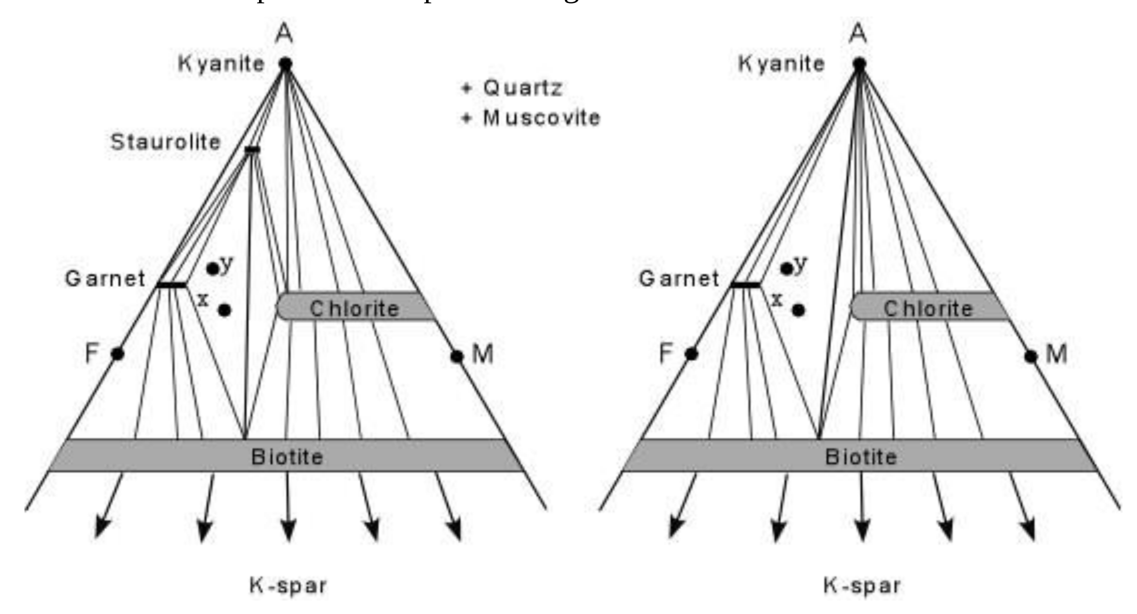
only apply to rocks with a composition similar to composition x.

Note that a rock with a composition slightly above x and above the Garnet - Chlorite tie line, like composition y in the AFM diagrams above, would still have a different mineral assemblage above the isograd, but it would be one that contained Staurolite below the isograd, but Biotite above the isograd. So for these rocks we would probably call the isograd the Biotite isograd. Because it would be called the Staurolite isograd for one group of rocks, but the Biotite isograd for another, and because Staurolite would occur in some rocks below the isograd and in other rocks only above the isograd, it would soon become very confusing.



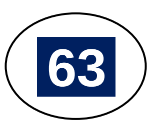
For these rocks the reaction boundary would really represent the disappearance of Chlorite. But since isograds are generally named for the appearance of a mineral with increasing grade, we can't call the reaction boundary the Chlorite Isograd because Chlorite is found in rocks of decreasing grade.

Another type of univariant reaction, however represents a reaction that is terminal to a mineral phase for a wide variety of compositions. Let's consider what happens in these same pelitic rocks if we reach a temperature and pressure region where staurolite becomes unstable.



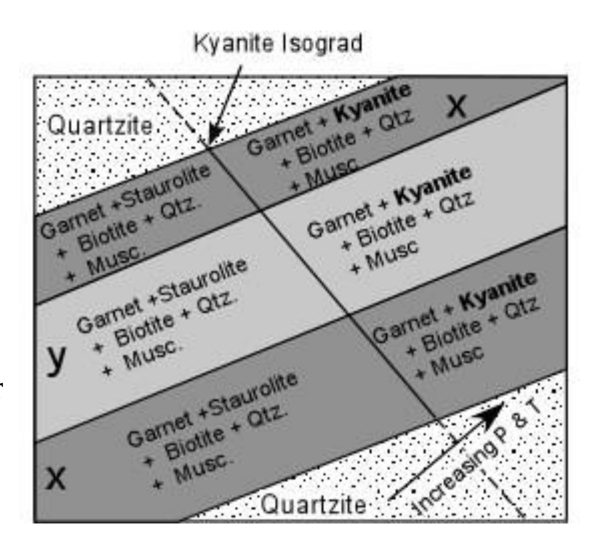
In this case, with increasing temperature, Staurolite becomes unstable and reacts to produce Garnet, Biotite and Kyanite. Notice that both rock compositions x and y have the same mineral assemblages before and after the reaction, although the proportions of the different minerals will be different in the two rocks. The reaction that is terminal to Staurolite can be written as:

Staurolite + Quartz + Muscovite <=> Garnet + Biotite + Kyanite + H_2O



Note that for this reaction the disappearance of staurolite also coincides with the appearance of Kyanite in rocks of composition x and y. If we were to encounter this reaction in the field, it could be used to define the Kyanite Isograd.

Note that the Kyanite Isograd as shown here would not be seen in a non-pelitic rock such as the quartzite, but could be extrapolated across the quartzite to other outcrops of pelitic rocks.



Note also, that in this diagram, the direction of increasing pressure and temperature during metamorphism was not parallel to the strike of the original rocks, just as a reminder that direction of increasing grade does not need to coincide with any particular orientation of the rocks.

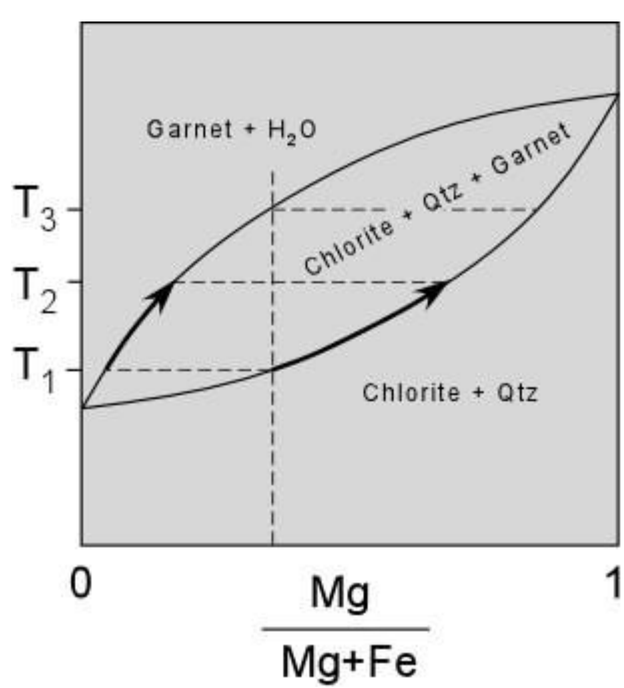
Divariant Reactions:

In the cases discussed above, the univariant reactions that were considered involved reaching a point in pressure temperature space where a reaction occurred resulting in a sudden change in mineral assemblage. These reactions can be considered discontinuous reactions because they occur along specific pressure temperature curves. Because many minerals are solid solutions, it is also possible to have discontinuous reactions that result in a gradual change in composition of the minerals, but not necessarily the formation of new minerals. These reactions are also considered divariant reactions because they occur over a wide range of pressure and temperature conditions. Consider the hypothetical case of rocks that contain minerals like chlorite and garnet, which are both Mg-Fe solid solutions.

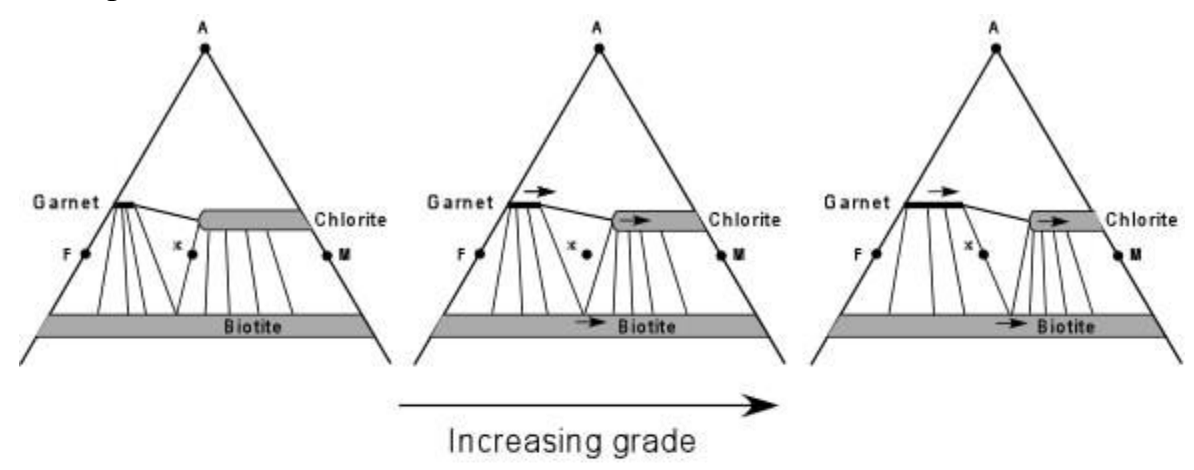
The reaction that occurs with increasing temperature (at constant pressure) is:

Chlorite + Qtz => Garnet + Mg-richer Chlorite + H_2O

This reaction begins at a temperature of T_1 where an initial Mg-poor garnet is produced. As temperature increases, say to T_2, both the garnet and the chlorite become more Mg-rich. The reaction continues over a range of temperature until eventually the temperature reaches T_3 at which point the much more Mg-rich chlorite disappears leaving garnet with Mg/(Mg/Fe) ratio the same as that in the initial chlorite. We say that this reaction is a continuous reaction because there is no change in mineral assemblage between T_1 and T_3, but there is a reaction occurring and its effect is to change the compositions of the solid solution minerals. Note the similarity of this idea to the melting behavior of Fe-Mg solid solution minerals, and the similarity to the concept of the continuous reaction series discussed with regard to Bowen's reaction series for magmas (where it involved changes in plagioclase composition).



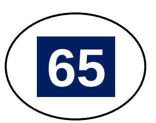
In a more realistic situation we can see how this occurs in relation to a similar reaction on an AFM diagram.



In the diagram to the left, representing the lowest grade, a rock with composition x consists of a relatively Mg-poor biotite + Mg-poor chlorite. As metamorphic grade increases to the middle diagram, the three phase triangle - Garnet - Biotite - Chlorite has shifted, with all three phases becoming more Mg-rich, and now composition x lies inside this 3 phase triangle, and thus now contains garnet. Further increase in metamorphic grade, causes further shift to of the apices of the 3 phase triangle toward more Mg-rich compositions and eventual disappearance of chlorite from the rock with composition x.

Note that throughout the changes in P & T, the proportion of the 3 phases in composition x will change, as will the composition of the Fe-Mg solid solution minerals. Although the appearance of Garnet will be sudden, the disappearance of chlorite will be gradual as P and T change. The reaction that is taking place in this case is:

Muscovite + Chlorite + Quartz <=> Mg-richer chlorite + Biotite +Garnet + H_2O



Metamorphic Reaction Mechanisms:

As we discussed previously, the fluid phase plays an important role in metamorphic reactions. Not only are fluid components necessary to form any hydrous or carbonate minerals, but the fluid phase can act as a catalyst for metamorphic reactions. We also noted above that the chemical reactions we write for the various transformations of mineral assemblages with increasing pressure and temperature are the net result of what actually took place. For example, we may deduce from a series of metamorphosed pelitic rocks that kyanite reacted to form sillimanite and the reaction:

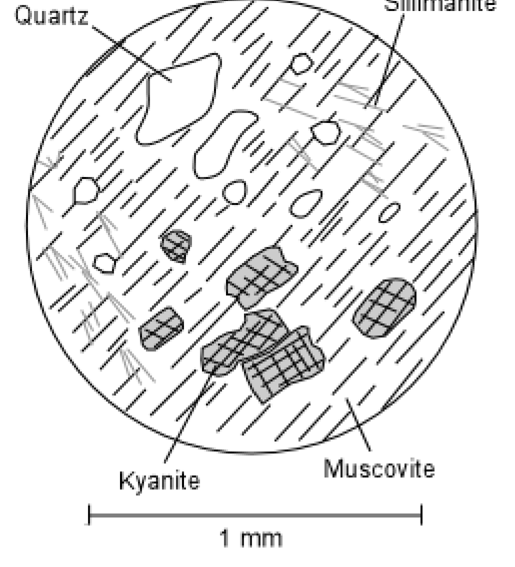
$$Al_2SiO_5 \Rightarrow Al_2SiO_5$$

Andalusite *Sillimanite*

must have occurred at some point during metamorphism. But, although this is the net reaction that must have occurred, we don't really know if the andalusite reacted directly to produce the sillimanite or if the andalusite was first dissolved in a fluid phase, with the fluid phase carrying the dissolved components to a new location where the fluid then precipitated the sillimanite. In general, solid-solid reactions run rather slowly because ions have to diffuse through the solids in order to rearrange themselves into new phases. Thus, it seems likely that the actual mechanisms or paths that a reaction takes will be more complicated than the net reaction implies.

If we can gain some insight into reaction mechanisms, then we may be better able to envision exactly how metamorphism operates in the Earth. Metamorphic petrologists can only rarely look through a rock and determine what actually happened.

One case where this seems to be possible is in series of metapelites in Canada. D.M. Carmichael examined thin sections of one particular metapelite that contains both kyanite and sillimanite. The rock shows no evidence that the sillimanite was forming directly from kyanite. Instead, examination of the rock in thin section shows that the kyanite has rounded edges and corners that could have formed as a result of dissolution. Similarly, some crystals of quartz in the rock show evidence dissolution. The sillimanite is found growing within flakes of muscovite. Thus, Carmichael deduced that in the area around where the kyanite crystals were dissolving the following reaction was taking place:



$$3Al_2SiO_5 + 3SiO_2 + 2K^+ + 3H_2O \Rightarrow 2KAl_3Si_3O_{10}(OH)_2 + 2H^+$$

Kyanite *Qtz* *fluid* *Muscovite*

Furthermore, in the small domains of the rock where sillimanite was forming in the muscovite, the following reaction was occurring:

$$2KAl_3Si_3O_{10}(OH)_2 + 2H^+ \Rightarrow 3Al_2SiO_5 + 3SiO_2 + 2K^+ + 3H_2O$$

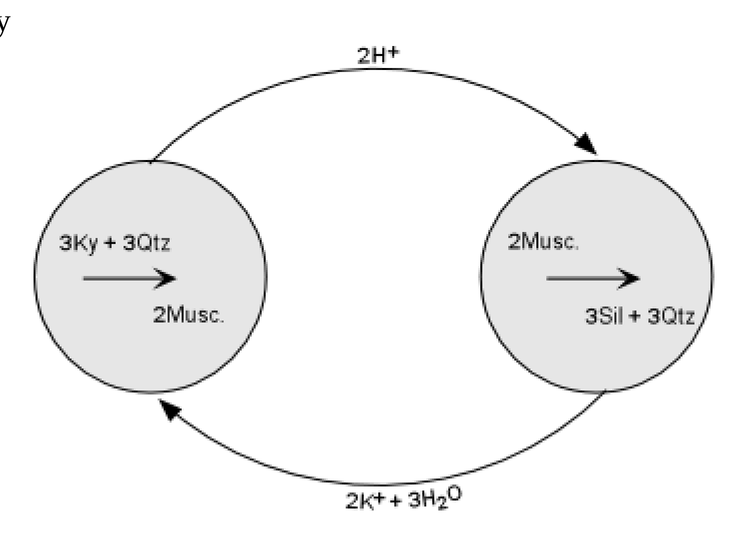
Muscovite *Sillimanite* *Qtz* *fluid*

Note that if these two reactions are added together algebraically, the net reaction is still:

$$Al_2SiO_5 \Rightarrow Al_2SiO_5$$

Andalusite *Sillimanite*

This makes sense, because Al is not very soluble in water, whereas K is soluble. Thus the fluid will be able to easily transport the K ions over short distances to supply that necessary to precipitate muscovite, and the growing sillimanite can use the Al left behind by the fluid. This reaction mechanism is shown diagrammatically in the diagram to the right. It implies that the two reactions were taking place simultaneously in different domains within the rock, and that the fluid phase was important in transferring ions from one domain to another, although over small distances.



Isograd Temperature Constraints

•Isogradic reactions at 4 kbar calibrated against Spear et al. (1999) petrogenetic Grid.

Garnet/Staurolite Zone(545°C)
Grt + Chl = St + Bt + H2O 2
Staurolite/Lower Sillimanite Zone(580°C)
St + Chl =Bt +Sil + HO
Lower /Upper Sillimanite Zone(620°C)
St = Grt + Bt + Sil + H2O
Upper Sillimanite/Sillimanite Zone(660°C)
Ms = Kfs + Sil + H2O

Metamorphic minerals:

Kyanite Al2SiO5 suggest high pressure in pelitic schist.

Sillimanite Al2SiO5 suggest high temperature in pelitic schist.

Andalusite Al2SiO5 suggests lower T & P in pelitic schist.

Chlorite (Mg,Fe).SiAl(OH) in green schist facies of basic rocks.

Chloritiod (ottrelite) (Fe,Mg),AlO found in Mg-rich politic rocks at high temperature and low pressure.

Zoisite CaAlSiO(OH) low T & P.

Lawsonite CaALSiO(OH).H2O low T & P.

Epidote CaFeAlSiO2(OH) at low and medium grade basic rocks.

Almandine garnet FeAlSiO.

Pyrope (Mg-garnet) MgAlSiO.

Grossular (Ca-garnet) CaAlSiO.

Biotite KMgFAlSiAlO(OH) at most metamorphic politic rocks.

Diopside CaMgSiO in metamorphosed calcareous and basic igneous rocks.

Jadeite NaFeSiO at high pressure metamorphic rocks.

Omphacite NaFeSiO (high pressure).

Wollastonite CaSiO high temperature of calcareous rocks.

Staurolite (Fe)AlSiO(OH) formed from Fe-rich politic rocks.

Tourmaline it is pneumatolitic mineral formed by the action of boron on pelitic and amphibolitic rocks by the solution from granitic magma. It is found through pneumatolitic granite (Na, Mg, Fe, Mn, Li, AlSiOBoO,OH).

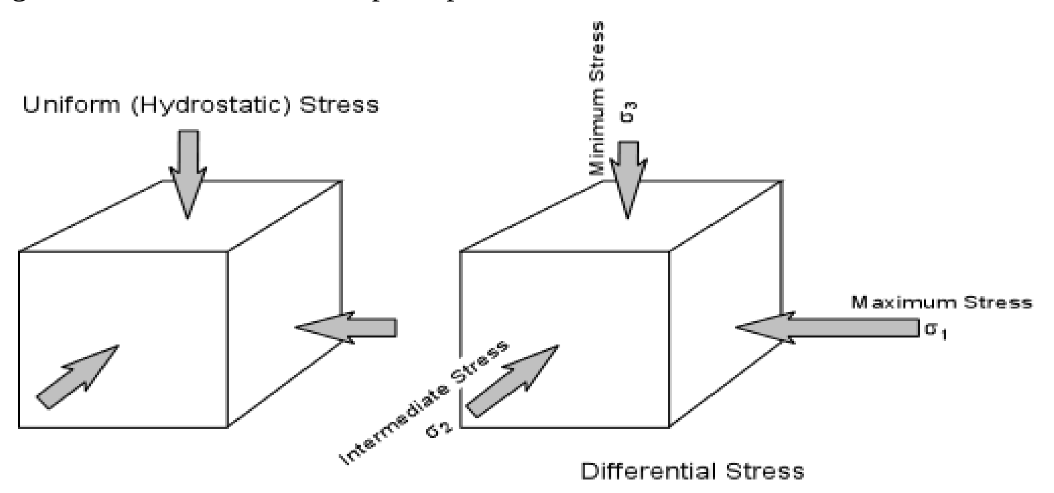
CHAPTER 5

Metamorphic Rock Textures

Metamorphic rocks exhibit a variety of textures. These can range from textures similar to the original protolith at low grades of metamorphism, to textures that are purely produced during metamorphism and leave the rock with little resemblance to the original protolith. Textural features of metamorphic rocks have been discussed in the previous lecture. Here, we concentrate on the development of foliation, one of the most common purely metamorphic textures, and on the processes involved in forming compositional layering commonly observed in metamorphic rocks.

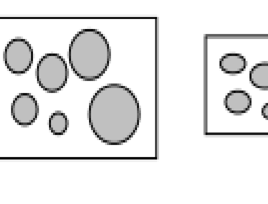
Stress and Preferred Orientation:

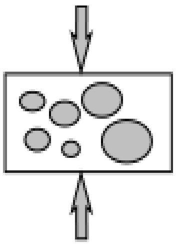
Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress*** or ***uniform stress.*** If the stress is not equal from all directions, then the stress is called a ***differential stress.*** Normally geologists talk about stress as compressional stress. Thus, if a differential stress is acting on the rock, the direction along which the maximum principal stress acts is called σ_1, the minimum principal stress is called σ_3, and the intermediate principal stress direction is called σ_2. Note that extensional stress would act along the direction of minimum principal stress.



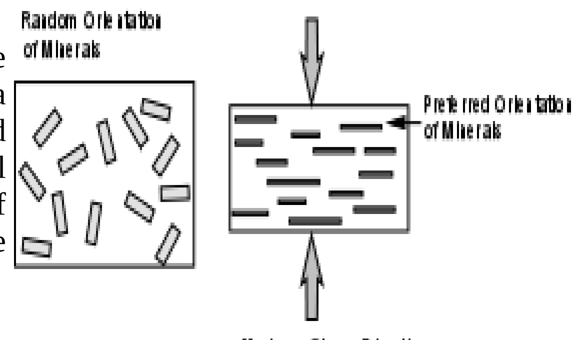
If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock.

- Rounded grains can become flattened in the direction of maximum compressional stress.





- Minerals that crystallize or grow in the differential stress field may develop a preferred orientation. Sheet silicates and minerals that have an elongated habit will grow with their sheets or direction of elongation orientated perpendicular to the direction of maximum stress.

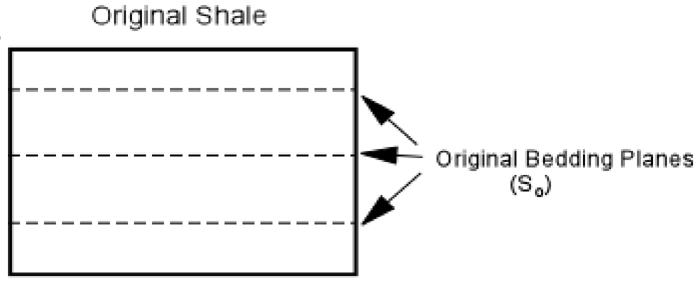


This is because growth of such minerals is easier along directions parallel to sheets, or along the direction of elongation and thus will grow along σ_3 or σ_2, perpendicular to σ_1.

Since most phyllosilicates are aluminous minerals, aluminous (pelitic) rocks like shales, generally develop a foliation as the result of metamorphism in a differential stress field.

Example - metamorphism of a shale (made up initially of clay minerals and quartz)

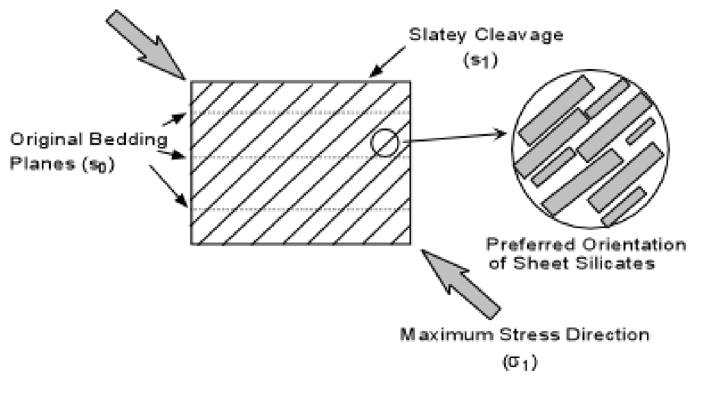
Shales have fissility that is caused by the preferred orientation of clay minerals with their {001} planes orientated parallel to bedding. Metamorphic petrologists and structural geologists refer to the original bedding surface as S_0.



- ## Slate:

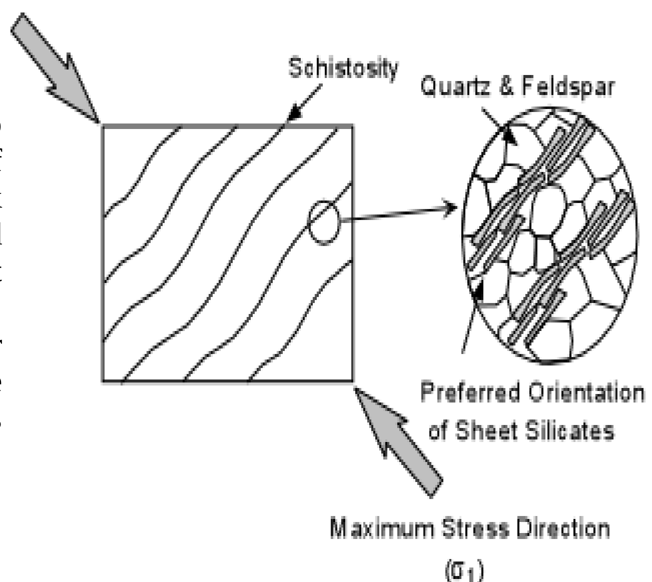
Slates form at low metamorphic grade by the growth of fine grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break planes parallel to the sheet silicates, causing a ***slatey cleavage.***

Note that in the case shown here, the maximum principle stress is oriented at an angle to the original bedding planes so that the slatey cleavage develops at an angle to the original bedding. The foliation or surface produced by this deformation is referred to S_1.



- ## Schist :

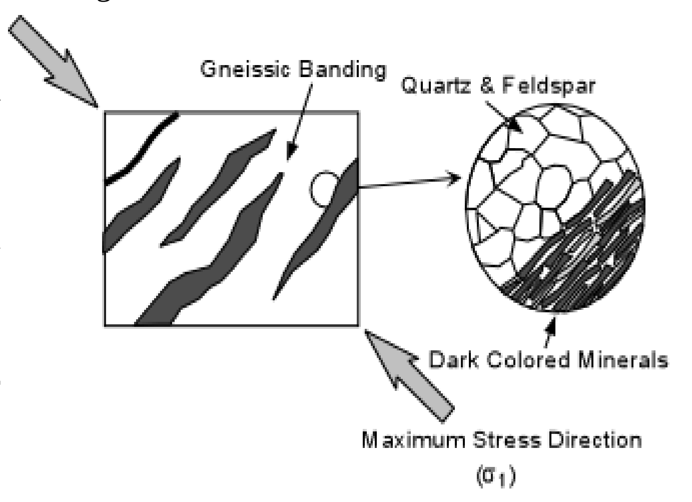
- The size of the mineral grains tends to enlarge with increasing grade of metamorphism. Eventually the rock develops a near planar foliation caused by the preferred orientation of sheet silicates (mainly biotite and muscovite). Quartz and feldspar grains, however show no preferred orientation. The irregular planar foliation at this stage is called ***schistosity***



- ## Gneiss:

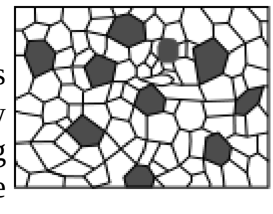
As metamorphic grade increases, the sheet silicates become unstable and dark colored minerals like hornblende and pyroxene start to grow.

These dark colored minerals tend to become segregated into distinct bands through the rock (this process is called metamorphic differentiation), giving the rock a ***gneissic banding***. Because the dark colored minerals tend to form elongated crystals, rather than sheet- like crystals, they still have a preferred orientation with their long directions perpendicular to the maximum differential stress.



- ## Granulite:

- At the highest grades of metamorphism most of the hydrous minerals and sheet silicates become unstable and thus there are few minerals present that would show a preferred orientation. The resulting rock will have a granulitic texture that is similar to a phaneritic texture in igneous rocks.

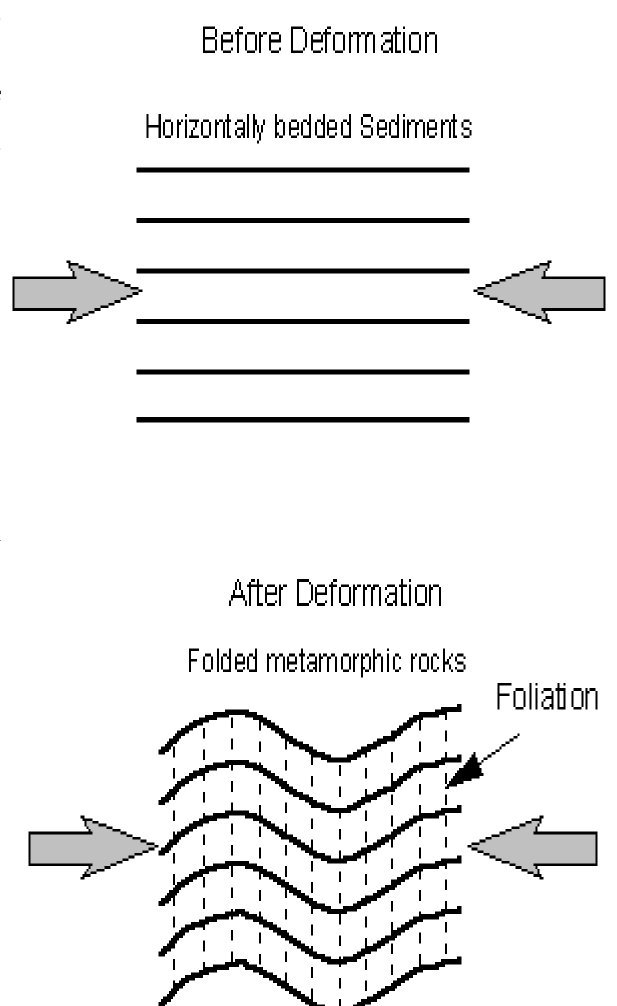


In general, the grain size of metamorphic rocks tends to increase with increasing grade of metamorphism, as seen in the progression form fine grained shales to coarser (but still fine) grained slates, to coarser grained schists and gneisses.

Metamorphism and Deformation:

Most regionally metamorphosed rocks (at least those that eventually get exposed at the Earth's surface) are metamorphosed during deformational events. Since deformation involves the application of differential stress, the textures that develop in metamorphic rocks reflect the mode of deformation, and foliations or slatey cleavage that develop during metamorphism reflect the deformational mode and are part of the deformational structures.

The deformation involved in the formation of fold-thrust mountain belts generally involves compressional stresses. The result of compressional stress acting on rocks that behave in a ductile manner (ductile behavior is favored by higher temperature, higher confining stress [pressure] and low strain rates) is the folding of rocks. Original bedding is folded into a series of anticlines and synclines with fold axes perpendicular to the direction of maximum compressional stress. These folds can vary in their scale from centimeters to several kilometers between hinges. Note that since the axial planes are oriented perpendicular to the maximum compressional stress direction, slatey cleavage or foliation should also develop along these directions. Thus, slatey cleavage or foliation is often seen to be parallel to the axial planes of folds, and is sometimes referred to axial plane cleavage or foliation.



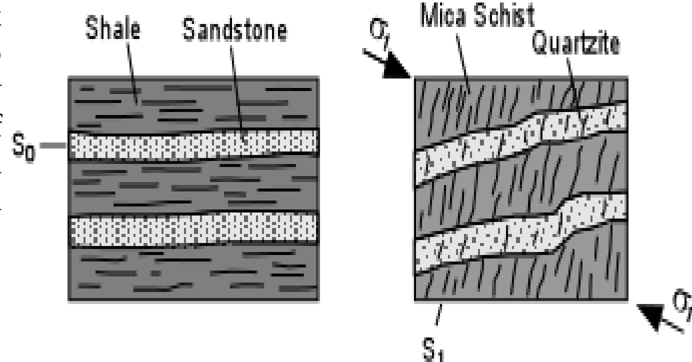
Metamorphic Differentiation:

As discussed above, gneisses, and to some extent schists, show compositional banding or layering, usually evident as alternating somewhat discontinuous bands or layers of dark colored ferromagnesian minerals and lighter colored quartzo-feldspathic layers. The development of such compositional layering or banding is referred to as ***metamorphic differentiation.*** Throughout the history of metamorphic petrology, several mechanisms have been proposed to explain metamorphic differentiation.

1. Preservation of Original Compositional Layering:

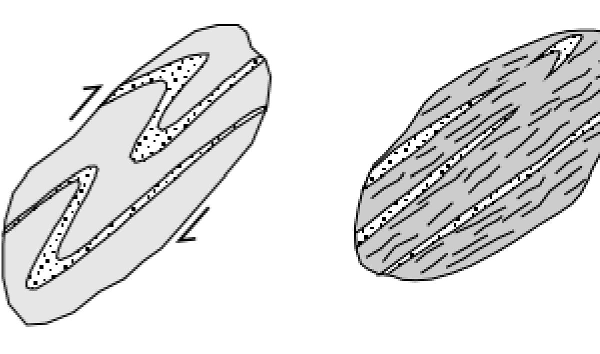
. In some rocks the compositional layering may not represent metamorphic differentiation at all, but instead could simply be the result of original bedding. For example, during the early stages of metamorphism and deformation of interbedded sandstones and shales the compositional layering could be preserved even if the maximum compressional stress direction were at an angle to the original bedding.

In such a case, a foliation might develop in the shale layers due to the recrystallization of clay minerals or the crystallization of other sheet silicates with a preferred orientation controlled by the maximum stress direction.



Here, it would be easy to determine that the compositional layers represented original bedding because the foliation would cut across the compositional layering.

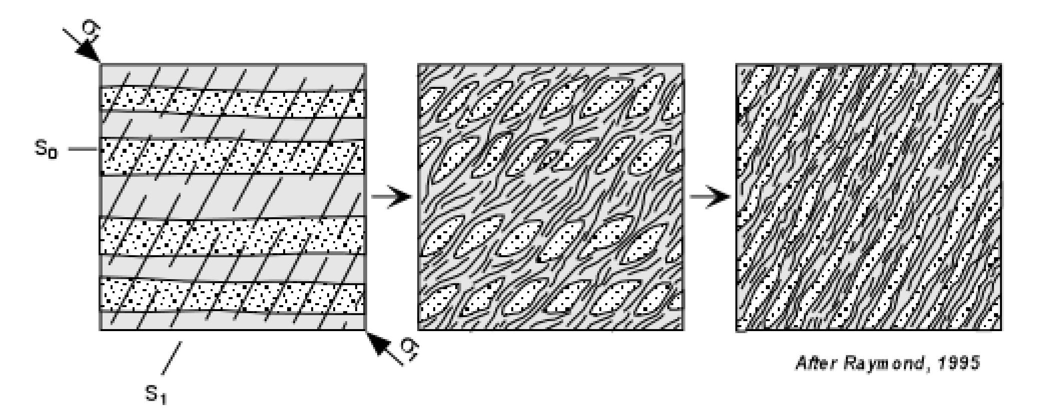
In highly deformed rocks that have undergone both folding and shearing, it may be more difficult to determine that the compositional layering represents original bedding. As shearing stretches the bedding, individual folded beds may be stretched out and broken to that the original folds are not easily seen.



Similarly, if the rock had been injected by dikes or sills prior to metamorphism, these contrasting compositional bands, not necessarily parallel to the original bedding, could be preserved in the metamorphic rock.

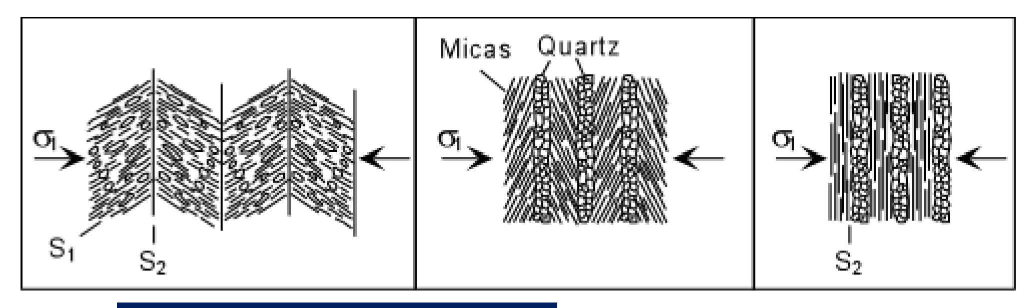
2. Transposition of Original Bedding:

Original compositional layering a rock could also become transposed to a new orientation during metamorphism. The diagram below shows how this could occur. In the initial stages a new foliation begins to develop in the rock as a result of compressional stress at some angle to the original bedding. As the minerals that form this foliation grow, they begin to break up the original beds into small pods. As the pods are compressed and extended, partly by recrystallization, they could eventually intersect again to form new compositional bands parallel to the new foliation.



3- Solution and Re-precipitation:

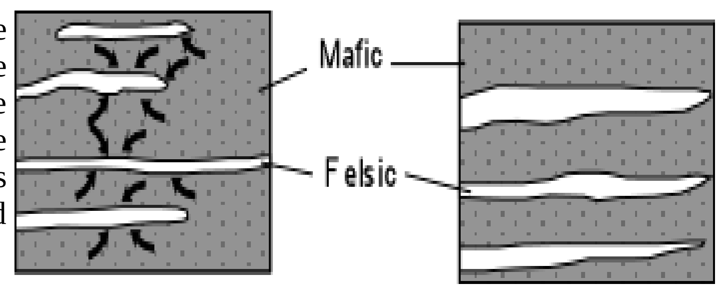
In fine grained metamorphic rocks small scale folds, called kink bands, often develop in the rock as the result of application of compressional stress. A new foliation begins to develop along the axial planes of the folds. Quartz and feldspar may dissolve as a result of pressure solution and be reprecipitated at the hinges of the folds where the pressure is lower. As the new foliation begins to align itself perpendicular to σ_1, the end result would be alternating bands of micas or sheet silicates and quartz or feldspar, with layering parallel to the new foliation.



4. Preferential Nucleation:

Fluids present during metamorphism have the ability to dissolve minerals and transport ions from one place in the rock to another.

Thus felsic minerals could be dissolved from one part of the rock and preferentially nucleate and grow in another part of the rock to produce discontinuous layers of alternating mafic and felsic compositions.



5. Migmatization:

. As discussed previously, migmatites are small pods and lenses that occur in high grade metamorphic terranes that may represent melts of the surrounding metamorphic rocks. Injection of the these melts into pods and layers in the rock could also produce the discontinuous banding often seen in high grade metamorphic rocks. The process would be similar to that described in 4, above, except that it would involve partially melting the original rock to produce a felsic melt, which would then migrate and crystallize in pods and

layers in the metamorphic rock. Further deformation of the rock could then stretch and fold such layers so that they may no longer by recognizable as migmatites.

Texture is divided into two groups**. Foliated textures** show a distinct planar character. This means that the minerals in the rock are all aligned with each other. This planar character can be flat like a piece of slate or folded. **Non-foliated textures** have minerals that are not aligned. Essentially, the minerals are randomly oriented.

Foliated textures:

show four types of foliation. **Slaty cleavage** is composed of platy minerals that are too small to see. Typically, these rocks split along parallel, planar surfaces. **Phyllitic foliation** is composed of platy minerals that are slightly larger than those found in slaty cleavage, but generally are still too small to see with the unaided eye. The larger size gives the foliation a slighly shiny appearance. **Schistose foliation** is composed of larger minerals which are visible to the unaided eye. Platy minerals tend to dominate. **Gneissic banding** is the easiest of the foliations to recognize. It is composed of alternating bands of dark and light minerals.

As was the case with igneous rocks, the primary parameter of classification among the metamorphic rocks is texture. Textures exhibited by metamorphic rocks are broadly defined as either foliated or non-foliated. Those rocks described to possess a foliated texture are formed from aligned mineral grains. Such alignment of elongated or platy grains will only occur under the influence of directed pressure. Thus, foliated metamorphic rocks are the product of the interaction of lithospheric plates and as such compose a significant part of the Earth's major mountain chains.

Non-foliated metamorphic rocks are formed from mineral grains lacking any particular alignment. Such random arrangement of minerals occurs during metamorphism in two ways. First, when rocks are exposed to elevated temperatures – in the absence of any directed forces – mineral grains are free to grow with any orientation. Thus, non-foliated rocks are always produced by lithostatic pressure. However, non-foliated rocks can also form in another way. If the precursor rock consists of equant sized grains – grains with shapes that have similar lengths, widths, and heights – then the application of directed force fails to produce any preferential orientation. Thus, rocks containing largely spherical or cubical shaped grains will not produce a foliated texture, no matter the intensity of the directed pressure. This is a critical difference. Foliated metamorphic rocks only form under conditions of directed pressure. Lithostatic pressure will only produce non-foliated metamorphic rocks. However, non-foliated metamorphic rocks can also form under conditions of directed pressure, when the precursor grains are equant in shape.



Temperature and pressure are the two controlling physical parameters responsible for altering the texture and composition of a metamorphic rock. However, there is a third critical factor that determines a rock's lithologic characteristics – the texture and composition of the precursor rock. All metamorphic rocks are formed from some preexisting rock – either sedimentary, metamorphic, or igneous. As such, the physical and chemical characteristics of the original rock have a profound influence upon the nature of the rock after metamorphism.

Low Grade

Slate - realigned clay minerals

Phyllite - chlorite and mica

Schist - micas and accessory minerals

Gneiss - bands of quartz, feldspar, mica

High Grade

The largest and most important groupings of metamorphic rocks are those displaying a foliated texture. Formed under conditions of directed stress, foliated metamorphic rocks exhibit four distinct types of aligned textures. At the lowest metamorphic grade is the foliated metamorphic rock slate. Slate generally forms by the realignment of clay minerals in the precursor rock shale at low temperatures and pressures. Slate is denser, and more resistant to erosion, than is shale. Additionally, the alignment of the clay crystals causes the rock to break along extremely flat and smooth surfaces – a property described as rock cleavage. In order of increasing metamorphic grade, the second rock type is phyllite. These chlorite-rich foliated rocks are commonly dark green in color, with a slight sheen or luster due to the cleavages of the sheet silicate mineral cholorite. One of the most abundant and important foliated metamorphic rocks is schist. Schist consists predominantly of micas but also commonly contains several important accessory minerals useful as thermometers and barometers of metamorphic conditions. Finally, at highest metamorphic grade is the rock gneiss. This foliated rock consists of alternating bands of quartz,

feldspar, and micas. There are two important trends within these foliated metamorphic rocks. With increasing metamorphic grade the intensity of the foliation increases. Likewise, at higher grade, the rocks are typically coarser grained.

Foliated Metamorphic Rocks:

Foliated metamorphic rocks are formed within the Earth's interior under extremely high pressures that are unequal, occurring when the pressure is greater in one direction than in the others (directed pressure). This causes the minerals in the original rock to reorient themselves with the long and flat minerals aligning perpendicular to the greatest pressure direction. This reduces the overall pressure on the rock and gives it a stripped look.

Foliated metamorphic rocks are identified on the basis of their texture:

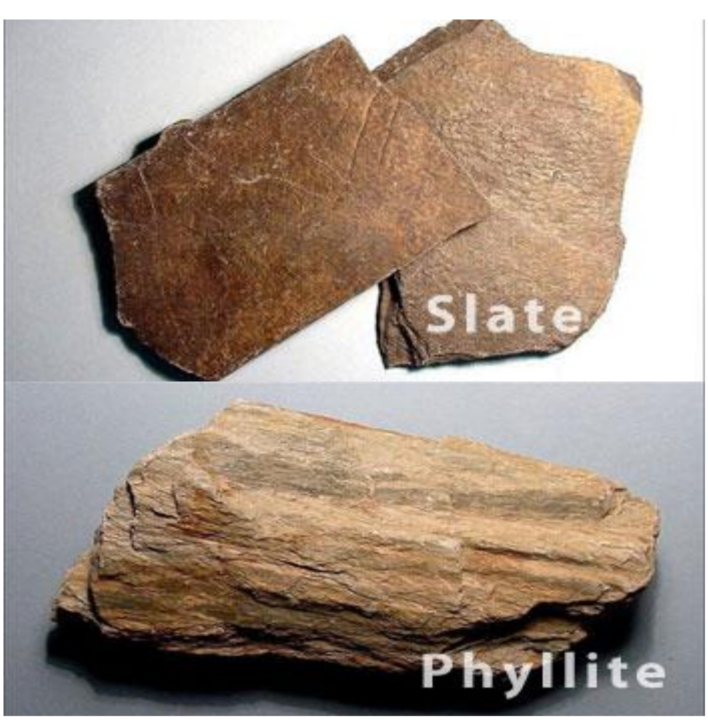
Slate = formed at very low temperatures and pressures, rock breaks along nearly perfect parallel planes; used in pool tables and as roofing material

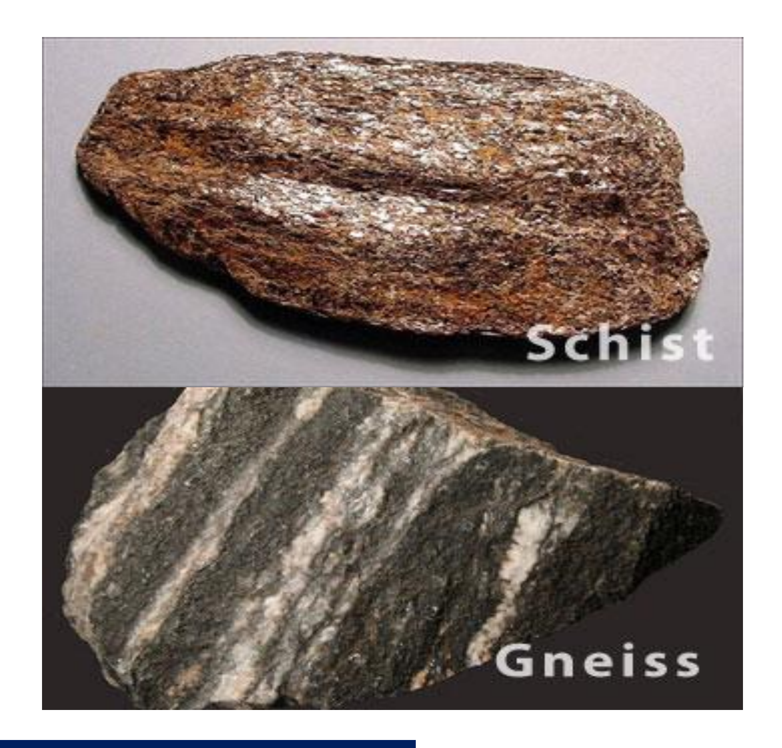
Phyllite = low to intermediate temperatures and pressures; slightly more crystallized which gives the rock a shiny appearance; layers may also be wavy or crinkled

Schist = intermediate to high temperatures and pressures; crystals are larger with the grains aligned in parallel to subparallel layers

Gneiss (nice) = very high temperatures and pressures; coarse grained texture of alternating light and dark mineral bands







Non-foliated textures:

Are identified by their lack of planar character. Further identification of non-foliated rocks is dependent on the composition of the minerals or components in the rock.

Granofels: a comprehensive term for any isotropic rock (a rock with no preferred orientation)

Hornfels is a type of granofels that is typically very fine-grained and compact, and occurs in contact aureoles. Hornfelses are tough, and tend to splinter when broken.


Hornfels

Marble: a metamorphic rock composed predominantly of calcite or dolomite. The protolith is typically limestone or dolostone.


Marble

Quartzite: a metamorphic rock composed predominantly of quartz. The protolith is typically sandstone. Some confusion may result from the use of this term in sedimentary petrology for a pure quartz sandstone.


Quartzit

Metamorphic Rock Identification Chart					
TEXTURE	FOLIATION	COMPOSITION	TYPE	PARENT ROCK	ROCK NAME
Foliated	slaty	mica	Regional	Mudstone	Slate
	phyllitic	quartz, mica, chlorite	Regional	Mudstone	Phyllite
	schistose	mica, quartz	Regional	Slate	Schist
	schistose	amphibole, plagioclase	Regional	Basalt or Gabbro	Amphibolite
	gneissic banding	feldspar, mica, quartz	Regional	Schist	Gneiss
Non-Foliated		carbon	Contact or Regional	Bituminous Coal	Anthracite Coal
		quartz, rock fragments	Contact or Regional	Conglomerate	Metaconglomerate
		calcite	Contact or Regional	Limestone	Marble
		quartz	Contact or Regional	Sandstone	Quartzite

Texture of metamorphic rocks:

Categories of Metamorphism:

Metamorphic rocks are divided on the basis of their field occurrence into the following categories:

1- Contact (Thermal) Metamorphism:

It is the recrystallization of rocks near the contacts of igneous intrusions due to rise in temperature. The area surrounding an intusive body is called contact aurole.

2 - Regional (Orogenic) Metamorphism:

This type outcrops over large areas and in a variety of settings. Rocks subjected to regional metamorphism occur in a great belt, hundreds or thousands of kilometers long and wide. Metamorphism produced as a result of the progressive increase in temperature and pressure, i.e. by burial of a rock within the earth, is termed prograde metamorphism and in general terms is characterized by dehydration reactions, which release water. With increasing depth of burial the pressure and temperature of the material increases along the follwong gradients:
P gradient 3.5 kbar/10 km •T gradient 20-30°C/km.

3 - Pyrometamorphism:

It is recrystallization at high temperatures and takes place in felsic, mafic and ultramfic xenoliths included in volcanic rokcs. It is an extraordinary kinds of thermal metamorphism. It may produce partila melting. Buchite is a partially melted rock derived from shael or sandstone.

4-Ocean-Floor Metamorphism :

It is the recrystallzation of of deeper part of the basic and ultrabasic rocks of the oceanic crust, mainly beneath the crest of the mid-ocean ridges.



5-Hydrothermal Metamoprhism :

It is the recrystallization of rokcs under the influence of a hot fluid phase introduced from the outside, mainly in geothermal fields.

6-Cataclastic (dynamic, dislocation) Metamorphism :

It is the crushing and grinding of rocks as a result of fault movement

7 - Impact Metamorphism:

This type occurs near the impact size of large meteorites.

Textures and structures of metamorphic rocks:

The orientation and arrangement of minerals in metamorphic rocks differ in different rocks, though the regional metamorphic rocks have textural similarities, as do the contact metamoprhic rocks. At the same time, a single rock may contain several textures or textural elements. The most important textures are as follows:

Foliation:

(Give your remarks on each texture in lab. How it looks like?) It is a planar element in metamoprhic rocks. It is defined as the parallel arrangement or distribution of minerals which ncludes layring of different mineralogical composition as in a gneiss and parallel arrangement of platy minerals (schistosity) as in a schist, closed spaced fracture (slaty clevage). It is usually developed during metamorphism by direct pressure which cause differential movement or recrystallization.

Schistosity:

The parallel arrangment of tabular minerals (Mica, amphiboles…etc.) to give a more or less planar fissility. With decrease in grain size, this grades to slaty cleavage (slate). Stretched or flattened grains, such as in quartz in deformed quartzites, may also form schistosity.

Gneissosity:

The alternation of lighter and darker layers, such as micaceous or amhibole-ric layers with quartzfeldspathic layers. The term is often used to include metamorphic layering regardless of its origin.

Lineation :

The parallel alignment of linear elements in the rock. It includes aligned prismatic grains, aggregates of grains, axes of microfolds, and lines of intersection of two or more schistosities.

Prefered Orientation :

This denote parallelism of tabular or elongated grains, as in schistosity or lineation- equidimensional grains according to their crystal lattice orientations (e.g. c-axes in quartz).

Hornfelsic and Granoblastic:

This is a non-directional texture. Planar or prismatic grains if present, are not oriented. The term granoblastic is used for coarse-grained texture and hornflesic to finer-grained rocks.

Porphyroblastic :
Large crystals of a mineral grown in a s[illegible]m of smaller grains. It is comparable to phenocrysts in igneous rocks.

Poikiloblastic :
It is a porphyroblast containing numerous inclusions of one or more groundmass minerals enveloped during growth (equivalent to sieve texture in igneous rocks)

Helicitic texture :
Direction of an earlier foliation is reflected in curved lines of inclusions that are preserved within a porhphyroblast. Often S-shaped as might be formed by rolling of a porphyroblast during growth.

Corona (reaction rim) :
A new mineral forms as a rim around a mineral that is no longer in its field of stability (e.g., actinolite around augite).
Porphyroclast :
Coarse, strained, and broken crystals in a finer-grianed matrix.

Augen:
(eye-shaped) Lage eyes (porphyroclasts) of feldspar in a finer grained gneissic matrix.

Mylonitite :
Extremely granulated and streaked-out grains-typically foliated and containing ovoid relict crystals.

Catalcalstic :
Sheared and crushed rock fabric, not as extreme as mylonitic. Nature of the original rock is recognizable from the undestroyed fragments.

Flaser:
A cataclastic texture in which undestroyed eyes of the original rock swim in granulated streasks and laminae.

Granoblastic:
means equigranular, mosaic or hornfelsic texture.

Foliation:

Foliation is defined as a pervasive planar structure that results from the nearly parallel alignment of sheet silicate minerals and/or compositional and mineralogical layering in the rock. Most foliation is caused by the preferred orientation of phylosilicates, like clay minerals, micas, and chlorite. Preferred orientation develops as a result of non-hydrostatic or ***differential stress*** acting on the rock (also called ***deviatoric stress***). We here review the differences between hydrostatic and differential stress.



Folded foliation in a metamorphic rock :

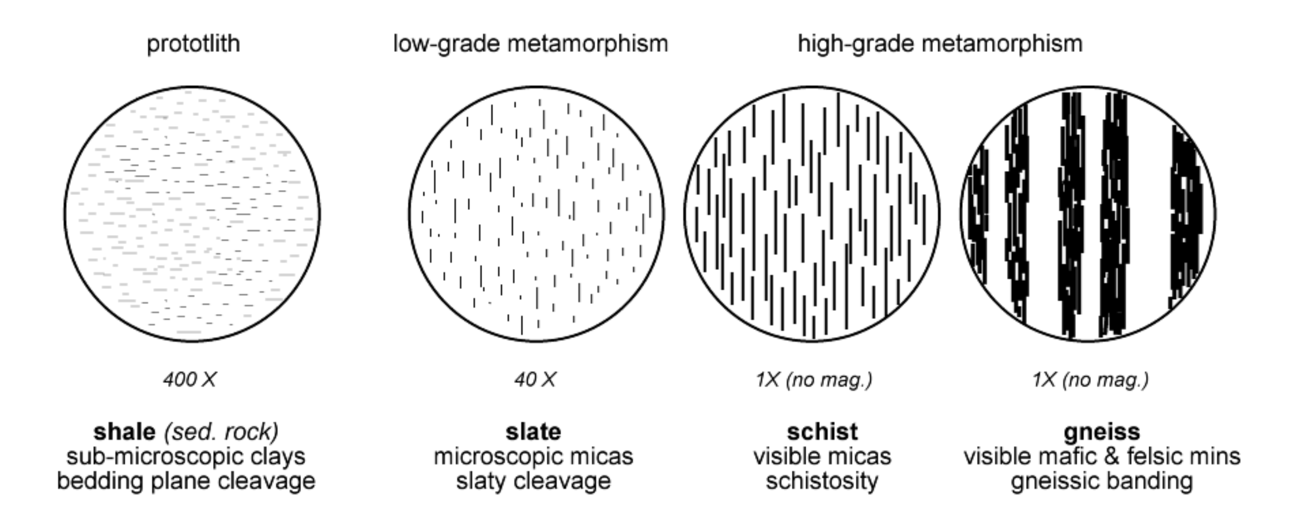
The layering within metamorphic rocks is called *foliation* (derived from the Latin word *folia*, meaning "leaves"), and it occurs when a rock is being shortened along one axis during recrystallization. This causes the platy or elongated crystals of minerals, such as mica and chlorite, to become rotated such that their long axes are perpendicular to the orientation of shortening. This results in a banded, or foliated rock, with the bands showing the colors of the minerals that formed them.

Textures are separated into foliated and non-foliated categories. Foliated rock is a product of differential stress that deforms the rock in one plane, sometimes creating a plane of cleavage. For example, slate is a foliated metamorphic rock, originating from shale. Non-foliated rock does not have planar patterns of strain.

Rocks that were subjected to uniform pressure from all sides, or those that lack minerals with distinctive growth habits, will not be foliated. Slate is an example of a very fine-grained, foliated metamorphic rock, while phyllite is medium, schist coarse, and gneiss very coarse-grained. Marble is generally not foliated, which allows its use as a material for sculpture and architecture.

Another important mechanism of metamorphism is that of chemical reactions that occur between minerals without them melting. In the process atoms are exchanged between the minerals, and thus new minerals are formed. Many complex high-temperature reactions may take place, and each mineral assemblage produced provides us with a clue as to the temperatures and pressures at the time of metamorphism.

Metasomatism is the drastic change in the bulk chemical composition of a rock that often occurs during the processes of metamorphism. It is due to the introduction of chemicals from other surrounding rocks. Water may transport these chemicals rapidly over great distances. Because of the role played by water, metamorphic rocks generally contain many elements absent from the original rock, and lack some that originally were present. Still, the introduction of new chemicals is not necessary for recrystallization to occur.



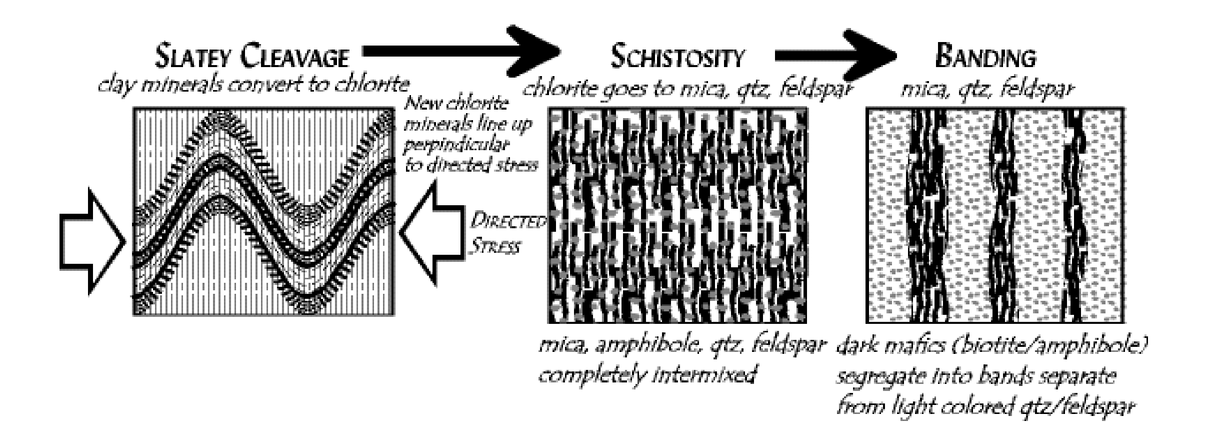
- Foliation: and planar fabric element.
- Lineation: any linear fabric elements.
  - They have no genetic connotations.
  - Some high-strain rocks may be foliated, but they are treated separately.

Cleavage:

- Traditionally: the property of a rock to split along a regular set of sub-parallel, closely-spaced planes.
- A more general concept adopted by some geologists is to consider cleavage to be any type of foliation in which the aligned platy phyllosilicates are too fine grained to see individually with the unaided eye .

Schistosity :

- A preferred orientation of inequaint mineral grains or grain aggregates produced by metamorphic processes.
- Aligned minerals are coarse grained enough to see with the unaided eye.
- The orientation is generally planar, but linear orientations are not excluded .





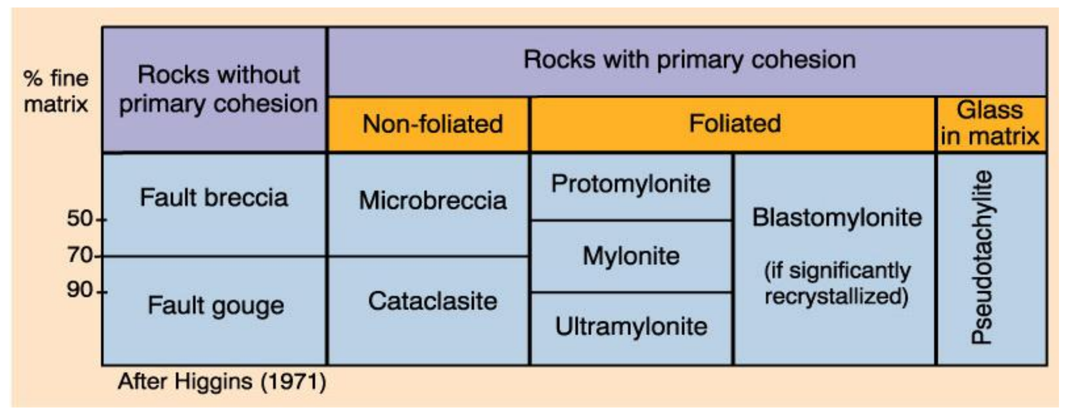
Gneissose structure:

- Either a poorly-developed schistosity or segregated into layers by metamorphic processes.
- Gneissose rocks are generally coarse grained .

- **Porphyroblastic** means that a metamorphic rock has one or more metamorphic minerals that grew much larger than the others. Each individual crystal is a porphyroblast .
- Some porphyroblasts, particularly in low-grade contact metamorphism, occur as ovoid “spots” .
- If such spots occur in a hornfels or a phyllite (typically as a contact metamorphic overprint over a regionally developed phyllite), the terms spotted hornfels, or spotted phyllite would be appropriate.
- **Some gneisses** have large eye-shaped grains (commonly feldspar) that are derived from pre-existing large crystals by shear (as described in Section 23.1). Individual grains of this sort are called auge (German for *eye*), and the (German) plural is augen. An augen gneiss is a gneiss with augen structure (Fig. 23-18).
- Ortho- a prefix indicating an igneous parent, and
- Para- a prefix indicating a sedimentary parent.



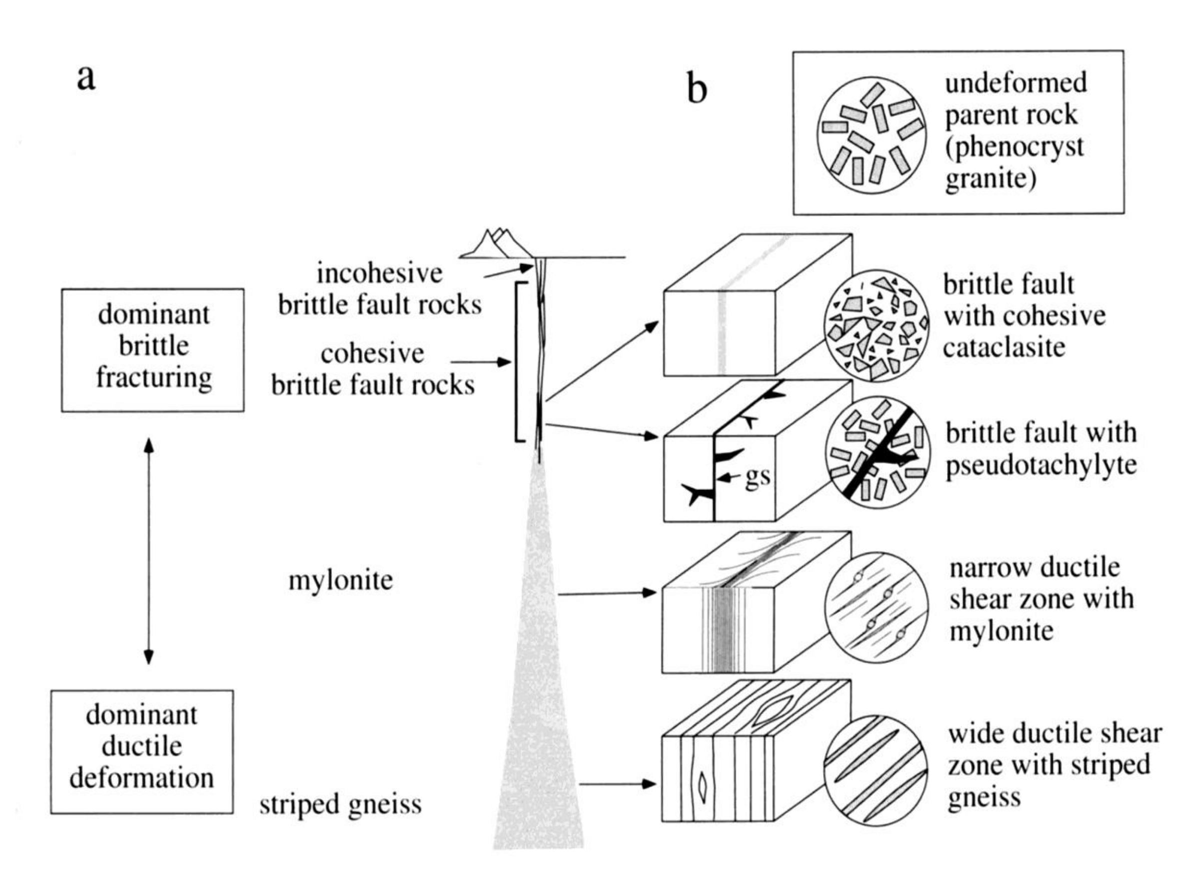
- The terms are used only when they serve to dissipate doubt. For example, many quartzo-feldspathic gneisses could easily be derived from either an impure arkose or a granitoid rock. If some mineralogical, chemical, or field-derived clue permits the distinction, terms such as *orthogneiss*, *paragneiss*, or *orthoamphibolite* may be useful.



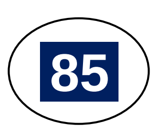
% fine matrix	Rocks without primary cohesion	Rocks with primary cohesion			
		Non-foliated	Foliated		Glass in matrix
	Fault breccia	Microbreccia	Protomylonite	Blastomylonite (if significantly recrystallized)	Pseudotachylite
50			Mylonite		
70	Fault gouge	Cataclasite			
90			Ultramylonite		

After Higgins (1971)

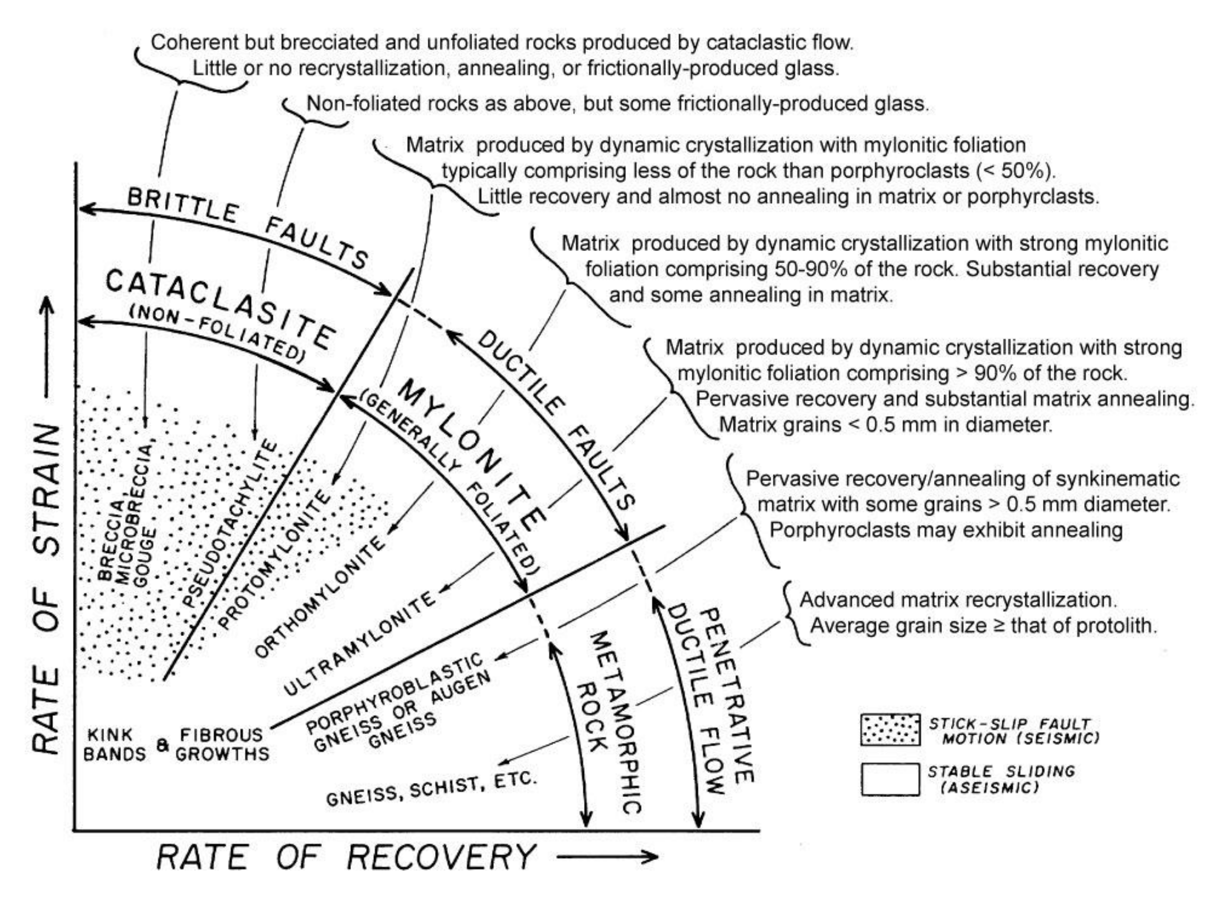
Classification of High-Strain- Fault Zone Rocks



Schematic cross section through a shear zone, showing the vertical distribution of fault-related rock types, ranging from non-cohesive gouge and breccia near the surface through progressively more cohesive and foliated rocks. Note that the width of the shear zone increases with depth as the shear is distributed over a larger area and becomes more ductile. Circles on the right represent



microscopic views or textures. From Passchier and Trouw (1996) *Microtectonics*. Springer-Verlag..



. Terminology for high-strain shear-zone related rocks proposed by Wise *et al*. (1984) Fault-related rocks: Suggestions for terminology. *Geology*, 12, 391-394.

Planar Foliated	Definition	IUGS term
Slaty cleavage	Aligned platy minerals, but grains too fine to see. Slate breaks in parallel sheets, which have earthy luster	aphanitic schist
Phyllitic	Phyllite breaks in parallel sheets, which have a more vitreous luster, sort of like silk	aphanitic schist with coarser grains
Schistose	Schist doesn’t break into sheets, but has aligned micas and visible mineral grains	phaneritic schist
Gneissic	Alternating bands of light and dark colored minerals	gneiss
Migmatitic	Mixed metamorphic rock and not-far-travelled magma	gneiss
Lineated Foliated	Oriented fabric marked by the alignment of needle-like (acicular) minerals, often amphibole.	phaneritic schist
Mylonitic	"Milled rock". Rock is crushed and smeared out in a fault zone. Like foliation without big xtls.	mylonite
Massive	none of the above	granofels

Structure+Texture	RockName	IUGS root name
Planar Foliated		
Slaty cleavage	Slate	aphanitic schist
Phyllitic	Phyllite	aphanitic schist
Schistose	Schist, with mineralogy	phaneritic schist
Gneissic	Gneiss, with mineralogy	gneiss
Migmatitic	Migmatite	gneiss
Lineated Foliated	treat as schist	phaneritic schist
Mylonitic	Mylonite	use separate scheme, or treat as schist, gneiss or granofels
Massive	Hornfels, quartzite, marble, veins	granofels

Structures of metamorphic rocks

يصعب التميز بين البنيات Structures والأنسجة textures في الصخور المتحولة نتيجة التداخل الشديد بينها وبين البنيات والأنسجة الأصلية القديمة بالاضافة الي أن الخور المتحولة قد تتعرض الي عمليات جيولوجية لاحقة تتسبب في تغيرات كبيرة في البنيات والأنسجة التحولية نفسها.

أهم أنواع البنيات التى يمكن ملاحظتها فى الصخور المتحولة هى:

1) البنية التحطمية (التركيب التهشمي)Cataclastic structure

بنية ناتجة من تكسر وتفتت مكونات الصخر الأصلية بفعل الاجهاد(الشد القصي) Shearing stress الناتج من الضغط والذي يتسبب في طحن بعض المكونات منتجاً ما يعرف بمسحوق البريشيا Breccias أو الميلونايت Mylonites.

2) البنية المنقطة (التركيب المنقط)Maculose structure

بنية تتكون نتيجة لوجود بلورات كبيرة ذات أشكال مكتملة من المعادن القوية مثل الأندالوسايت, الكورجيرايت والبيوتايت منتشرة في أرضية الصخر بدون انتظام حيث يظهر اصخور وكأنه منقط أو فيه بقع مميزة وخاصة اذا كانت البلورات داكنة اللون والأرضية فاتحة اللون او العكس. ينتشر مثل هذا التركيب في الصخور الطينية المتحولة بالتماس.

3) البنية الشستوزية (التركيب الشستوزى)Schistose structure

يظهر في الصخور المتحولة بفعل الحرارة والضغط (تحول اقليمي) وفيه تتخذ المعادن وخاصة القشرية Flaky, الصفائحية Tabular او الشبيهة بالقطبان Rot-like) مثل المايكا Mica, الكلورايت Chlorite, التلك Talc) أشكالاً طولية متصلة ومرتبة في اتجاه عمودي علي اتجاه الضغط فتتكون طبيقاتLayers او صفائح Folia مرتبة في حزم متوازيةParallel bands , وهذه الصفة تعرف بالصفائحية Foliation.

4) البنية الحبيبية (التركيب الحبيى)Granulose structure

يتكون الصخرالذي يمتلك البنية من حبيبات متساوية الأبعاد تقريبا وهذا يرجع لتأثير الضغط المنتظم وأهم المعادن التي تاخذ هذا الشكل هي الجارنت Garnet, الكالسايت Calcite, البروكسينPyroxene والكوارتز Quartz.

5) البنية النيسوزية (التركيب النيسوزى)Gneissose structure

يتكون بتداخل البنية الشستوزية والبنية الحبيبية مع بعضهما البعض ويظهر الصخر علي شكل رقائق غير متصلة أو عدسات من المعادن الصفائحية مع قطع منكسرة من المعادن القوية مثل الفلسبارات مكونة أشكالا تشبه العين.

الأنسجة فى الصخور المتحولة :
Textures of metamorphic rocks

يقصد بالنسيج في الصخور المتحولة مظهر الصخر العام من حيث حجم المكونات البلورية, الشكل, التوزيع والتوجيه.

يعتبر النسيج فى الصخور المتحولة عموماً نتاج ثلاث عوامل:

(أ) التبلور وإعادة التبلور: ويشمل تبلور لمعدن جديدة وإعادة التبلور لمعدن أصلية موجودة من قبل.

(ب) التشوه: عندما تتعرض الصخور الي ضغط عالي تتكسر الي أجزاء أو تتحول الي مسحوق .

(ج) الزمن: كل من عمليات التبلور وإعادة التبلور والتشوه تعتمد علي الزمن.

يمكن تقسيم الأنسجة فى الصخور المتحولة الى ثلاث أقسام:

(1) الأنسجة التحولية الجديدة .

2) Pydomorphic textures) الأنسجة الموروثة (المتبقية) .

3) Relict textures) الأنسجة ما بعد التحولية Post-.metamorphic textures .

تعتمد الأنسجة التحولية الجديدة فى تكوينها على:

* أشكال المعادن:

لكل معدن نمو بلورى متميز أثناء التبلور وإعادة التبلور معطياً شكلاً بلورياً خاصاً Crystal habit عليه تأخذ المعادن أشكالاً:

(i) الأشكال القشرية Platy/ flaky والصفا ئحية Lamellar:

وهي بلورات نامية بصورة حسنة في اتجاه وضعيفة في الثاني وتكاد تكون مع معدوم النمو في الأتجاه الثالث كما في الميكا Mica, الكلورايت Chlorite, والتلك Talc

(ii) الأشكال المنشورية :

تأخذ البلورة شكل المنشور كما في الهونيبلند Hornblende

(iii) الأشكال العمدانية Columnar والشبيهة بالقضبان Rot-like:

حيث يكون النمو قوي جداً في اتجاه بعد واحد من الابعاد الثلاثة.

(iv) الأشكال ذ ت الهيئات متساوية الابعاد:

معادن تتكون بتأثير الضغط الموجه حيث تكون الابعاد متساوية تقريباً ومن أمثلة هذا النوع معادن الكوارتز Quartzite, الفلسبار Feldspars, البروكسين Pyroxene والكالسايت Calcite

*** نمو بلورات المعادن والعلاقات المتبادلة بينها:**

يحصل نمو البلورات عملياً في أوساط صلبة وفي آن واحد ولا يوجد تعاقب في التبلور كما في الصخور النارية وتتكون نتيجة لهذا الأنواع التالية من الأنسجة:

أ) النسيج البلوري التحولي Crystalloblastic texture:

يتكون نتيجة لاعادة تبلور المعادن الأصلية بفعل الضغط والحرارة وتمتلك المعادن المكونة لهذا النسيج قوة بلورية عظمى تستطيع أن تفرض شكلها البلوري الخاص حتي ضد مقاومة الوسط الصلب وهو ينقسم الى قسميين:

Xenoblastic عندما تكون البلورات الناتجة عديمة الأوجه كما في الكوارتز, الأبيدوت والأمفيبول.

Idioblastic عندما تكون البلورات الناتجة ذات أشكال كاملة الأوجه كما في الجا:رنت, الكيانيت, الروتايل, الاسفين والمافنيتايت

ب) النسيج السماقي التحولي Porphyroplastic texture :

يتكون نتيجة لوجود بلورات كبيرة ذات أشكال كاملة مطمورة في أرضية صخرية مكونة من حبيبات صخرية ناعمة.

ج) النسيج الحبيبي التحولي Granoblastic texture:

عندما تشكل البلورات ذات الأبعاد المتساوية حبيبات ملحوظة في مظهر الصخر.

د) النسيج الاختراقي التحولي Ophistoblastic texture:

يعتبر هذا النوع بقايا لانسجة سابقة ويتكون عندما يكوّن نسيج الصخر بلورات متداخلة كبلورات البلاجيوكليز المتداخلة في بلورات الأوجايت.

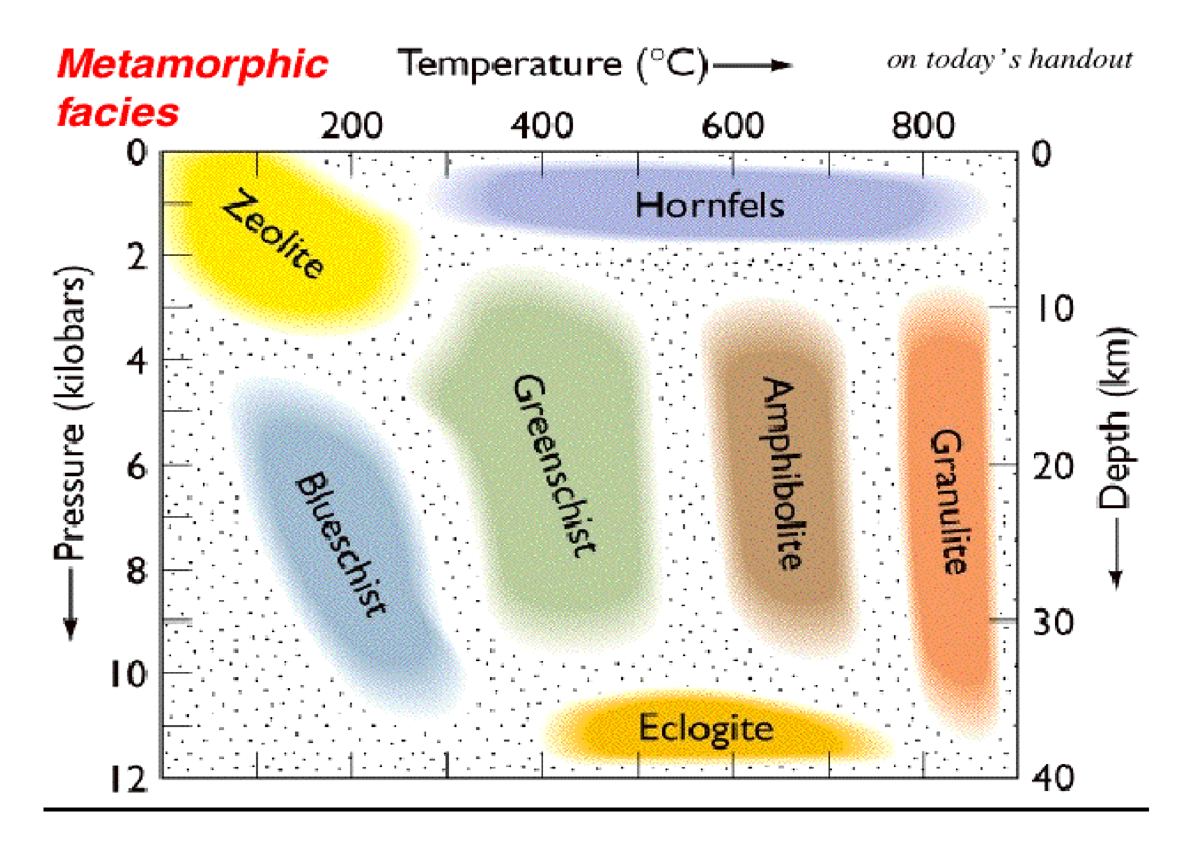
CHAPTER 6

Metamorphic Facies

Metamorphic facies are recognizable terranes or zones with an assemblage of key minerals that were in equilibrium under specific range of temperature and pressure during a metamorphic event. The facies are named after the metamorphic rock formed under those facies conditions from basalt. Facies relationships were first described by Pentti Eskola in 1921.

Metamorphic facies **-** An assemblage of minerals that reached equilibrium under a specific set of temperature and pressure conditions. Each facies named for a readily recognizable characteristic mineral or other feature. Remember that any one mineral does not have to be present, the facies is characterized by several different Facies:

1. Zeolite facies
2. Prehnite-pumpellyite-facies
3. Greenschist facies
4. Amphibolite-facies
5. Granulite facies
6. Blueschist facies
7. Eclogite facies
8. Albite-epidote-hornfels facies
9. Hornblende-hornfels facies
10. Pyroxene-hornfels facies
11. Sanidinite facies



- Low T - Low P : Zeolite
- Mod - High T - Low P : Prehnite-Pumpellyite
- Low T - High P : Blueschist
- Mod to High T - Mod P : Greenschist - Amphibolite - Granulite
- Mod - High T - High P : Eclogite

1- Zeolite - Transitional from sedimentary conditions. P 2-4 kb and T 200-300 degrees C.

2- Greenschist - Low temperature and pressure facies of regional metamorphism. P 3-8 kb and T 300-500 degrees C. Characterized by the green minerals chlorite, epidote and actinolite.

3- Amphibolite - Moderate to high temperature and low pressure regional metamorphic facies. P 3-8 kb and T 500-700 degrees C. Characterized by the presence of amphibole.

4- Granulite - High temperature and low to moderate pressure regional metamorphic facies. P 3-12 kb and T >650 degrees C. Characterized by quartz, feldspar, same minerals in a granite, hence the name.

5- Blueschist - Low temperature and high pressure metamorphic facies. Occurs only in areas of abnormally low geothermal gradients. P >4 kb and T 200-450 degrees C. Name from the blue mineral glaucophane. Common rock type on Catalina Island. Actually very rare in much of the world.

6- Eclogite - Mantle rock, probably not a valid metamorphic facies. Requires P >10 kb and T from 350-750 degrees C.



Metamorphic facies and their mineral assemblages:

Regional Metamorphic Facies:

Mountain systems typically contain large belts of regionally metamorphosed rock. These are often foliated metamorphic rocks developed under medium to high temperatures. They occur in belts of regional extent, from which the term regional metamorphism was originally derived. The accompanying pressures vary from low to high. Geothermal gradients, which are likewise moderate to high, produce Buchan and Barrovian Facies series. Because the pressures of Buchan and Barrovian Facies series are commonly higher than are those of Contact Facies Series, they may contain different sequences of minerals.

- Buchan Facies Series forms under pressures, which, in the middle grades of metamorphism, are *lower* than that of the aluminum silicate triple point. Consequently, the critical sequence of aluminum silicates is kaolinite -->pyrophyllite -->andalusite --> sillimanite.
- Barrovian Facies Series, in contrast, develops where pressures in the middle grades of metamorphism are *higher* than that of the aluminum silicate triple point. The resulting aluminum silicate mineral sequence is kaolinite -->pyrophyllite -->kyanite --> sillimanite.

The presence of either andalusite or kyanite on metamorphosed shales and siltstones at the middle grades of metamorphism is one feature that distinguishes these facies series from one another.

Zeolite facies:

The zeolite facies is the metamorphic facies with the lowest metamorphic grade. At lower temperature and pressure processes in the rock are called diagenesis. The facies is named for zeolites, strongly hydrated tectosilicates. It can have the following mineral assemblages:

In meta-igneous rocks and greywackes:

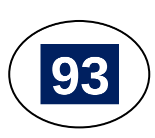
- heulandite + analcite + quartz ± clay minerals
- laumontite + albite + quartz ± chlorite

In metapelites:

- muscovite + chlorite + albite + quartz

Prehnite-pumpellyite-facies:

The prehnite-pumpellyite facies is a little higher in pressure and temperature than the zeolite facies. It is named for the minerals prehnite (a Ca-Al-phyllosilicate)



and pumpellyite (asorosilicate). The prehnite-pumpellyite is characterized by the mineral assemblages:

In meta-igneous rocks and greywackes:

- prehnite + pumpellyite + chlorite + albite + quartz
- pumpellyite + chlorite + epidote + albite + quartz
- pumpellyite + epidote + stilpnomelane + muscovite + albite + quartz

In metapelites:

- muscovite + chlorite + albite + quartz

Greenschist facies:

The greenschist facies is at medium pressure and temperature. The facies is named for the typical schistose texture of the rocks and green colour of the minerals chlorite, epidoteand actinolite. Characteristic mineral assemblages are:

In metabasites:

- chlorite + albite + epidote ± actinolite, quartz

In metagreywackes:

- albite + quartz + epidote + muscovite ± stilpnomelane

In metapelites:

- muscovite + chlorite + albite + quartz
- chloritoid + chlorite + muscovite + quartz ± paragonite
- biotite + muscovite + chlorite + albite + quartz + Mn-garnet (spessartine)

In Si-rich dolostones:

- dolomite + quartz

Amphibolite-facies:

The amphibolite facies is a facies of medium pressure and average to high temperature. It is named after amphiboles that form under such circumstances. It has the following mineral assemblages:

In metabasites:

- hornblende + plagioclase ± epidote, garnet, cummingtonite, diopside, biotit



In metapelites:

- muscovite + biotite + quartz + plagioclase ± garnet, staurolite, kyanite/sillimanite

In Si-dolostones:

- dolomite + calcite + tremolite ± talc (lower pressure and temperature)
- dolomite + calcite + diopside ± forsterite (higher pressure and temperature)

Granulite facies:

The granulite facies is the highest grade of metamorphism at medium pressure. The depth at which it occurs is not constant. A characteristic mineral for this facies and the pyroxene-hornblende facies is orthopyroxene. The granulite facies is characterized by the following mineral assemblages:

In metabasites:

- orthopyroxene + clinopyroxene + hornblende + plagioclase ± biotite
- orthopyroxene + clinopyroxene + plagioclase ± quartz
- clinopyroxene + plagioclase + garnet ± orthopyroxene (higher pressure)

In metapelites:

- garnet + cordierite + sillimanite + K-feldspar + quartz ± biotite
- sapphirine + orthopyroxene + K-feldspar + quartz ± osumilite (at very high temperature.

Blueschist facies:

The blueschist facies is at relatively low temperature but high pressure, such as occurs in rocks in a subduction zone. The facies is named after the schistose character of the rocks and the blue minerals glaucophane and lawsonite. The blueschist facies forms the following mineral assemblages:

In metabasites:

- glaucophane + lawsonite + chlorite + sphene ± epidote ± phengite ± paragonite, omphacite

In metagreywackes:

- quartz + jadeite + lawsonite ± phengite, glaucophane, chlorite



In metapelites:

- phengite + paragonite + carpholite + chlorite + quartz

In carbonate-rocks (marbles):

- aragonite

Eclogite facies:

The eclogite facies is the facies at the highest pressure and high temperature. It is named for the metabasic rock eclogite. The eclogite facies has the mineral assemblages:

In metabasites:

- omphacite + garnet ± kyanite, quartz, hornblende, zoisite

In metagranodiorite:

- quartz + phengite + jadeite/omphacite + garnet

In metapelites:

- phengite + garnet + kyanite + chloritoid (Mg-rich) + quartz
- phengite + kyanite + talc + quartz ± jadeite

Albite-epidote-hornfels facies:

The albite-epidote-hornfels facies is a facies at low pressure and relatively low temperatures. It is named for the two minerals albite and epidote, though they are also stable in other facies. Hornfels is a rock formed by contact metamorphism, a process that characteristically involves high temperatures but low pressures/depths. This facies is characterized by the following minerals:

In metabasites:

- albite + epidote + actinolite + chlorite + quartz

In metapelites:

- muscovite + biotite + chlorite + quartz

Hornblende-hornfels facies:

The hornblende-hornfels facies is a facies with the same low pressures but slightly higher temperatures as the albite-epidote facies. Though it is named for the mineral hornblende, the appearance of that mineral is not constrained to this facies. The hornblende-hornfels facies has the following mineral assemblages:

In metabasites:

- hornblende + plagioclase ± diopside, anthophyllite/cummingtonite, quartz

In metapelites:

- muscovite + biotite + andalusite + cordierite + quartz + plagioclase

In K_2O-poor sediments or meta-igneous rocks:

- cordierite + anthophyllite + biotite + plagioclase + quartz

In Si-rich dolostones:

- dolomite + calcite + tremolite ± talc

Pyroxene-hornfels facies:

The pyroxene-hornfels facies is the contact-metamorphic facies with the highest temperatures and is, like the granulite facies, characterized by the mineral orthopyroxene. It is characterized by the following mineral assemblages:

In metabasites:

- orthopyroxene + clinopyroxene + plagioclase ± olivine or quartz

In metapelites:

- cordierite + quartz + sillimanite + K-feldspar (orthoclase) ± biotite ± garnet

  (If the temperature is below 750°C there will be andalusite instead of sillimanite)

- cordierite + orthopyroxene + plagioclase ± garnet, spinel

In carbonate rocks:

- calcite + forsterite ± diopside, periclase
- diopside + grossular + wollastonite ± vesuvianite

Sanidinite facies:

The sanidinite facies is a rare facies of extremely high temperatures and low pressure. It can only be reached under certain contact-metamorphic circumstances. Due to the high temperature the rock experiences partial melting and glass is formed. This facies is named for the mineral sanidine. It is characterized by the following mineral assemblages:

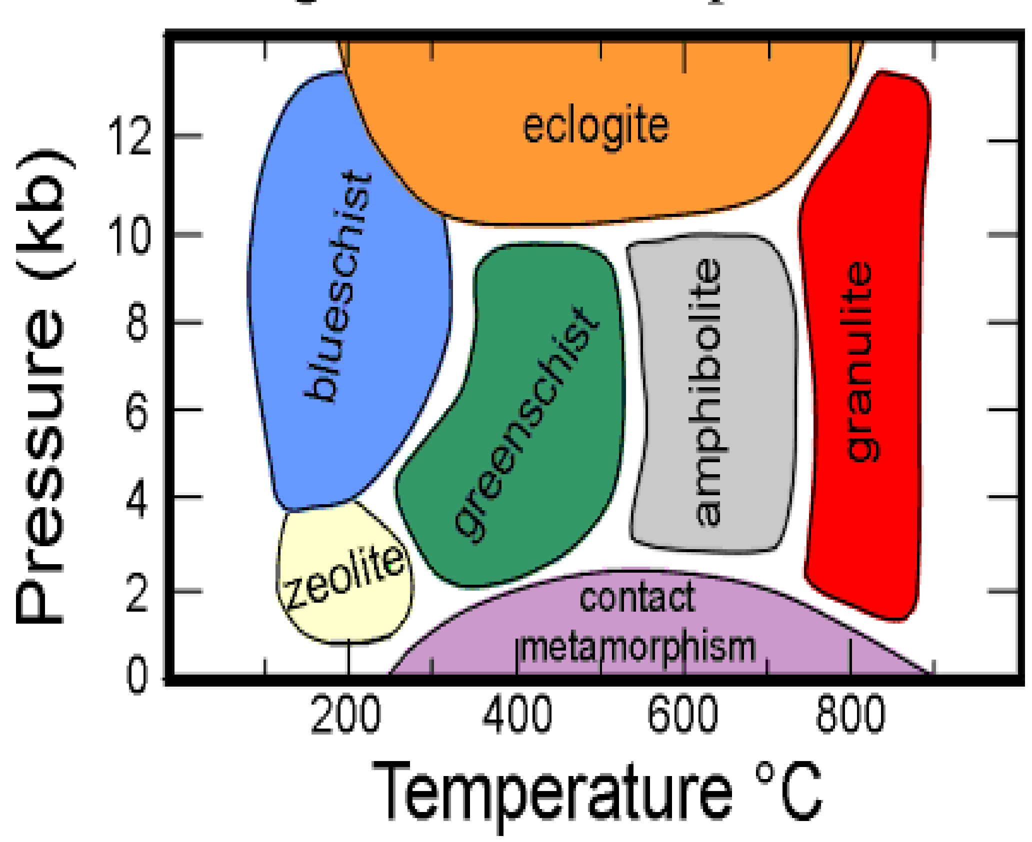
In metapelites:

- cordierite + mullite + sanidine + tridymite (often altered to quartz) + glass

In carbonates:

- wollastonite + anorthite + diopside
- monticellite + melilite ± calcite, diopside

(also tilleyite, spurrite, merwinite, larnite and other rare Ca- or Ca-Mg-silicates).



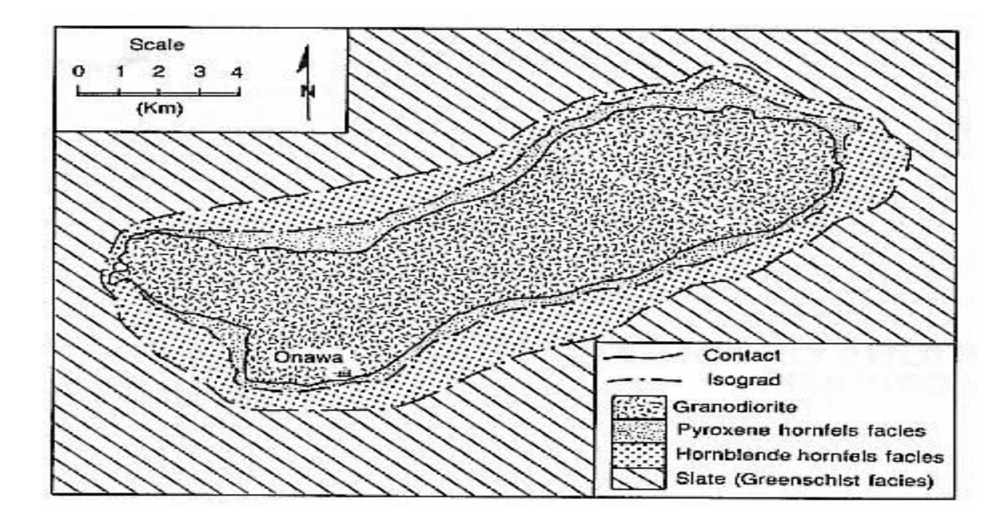
Contact Metamorphic Facies:

Contact metamorphism occurs locally, at and near the contacts between intrusions and the surrounding country or host rock. The heat introduced by the intrusion controls the metamorphism. The effects of increased temperature are most pronounced where intrusions occur at shallow levels. There, contrasts in temperature between country rock and intrusion are at a maximum. The fluid phase is also an important agent of contact metamorphism. It transports heat and has a profound influence on the chemistry and mineral composition of the rocks with which it comes in contact. Fluids are particularly important in the metamorphism of carbonate rocks. Contact metamorphism commonly produces fine-grained rocks termed *hornfels*. In addition to a variety of common minerals, such as quartz, feldspars, and epidote, hornfels locally contain unique phases. Typically, contact metamorphism occurs at shallower levels of the crust, where the pressure is relatively low (< 4 kb). At those shallow levels, the stresses characteristic of orogenic belts are generally absent and contact metamorphic rocks lack foliation .

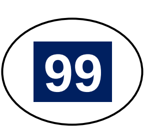
Contact Metamorphic Facies Series:

Contact metamorphic rocks are found in *aureoles*, zones of metamorphic rock surrounding and associated with plutons. Observation of the occurrences of contact metamorphic rocks reveals that Zeolite, Prehnite-Pumpellyite, Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite facies constitute the ***Contact Metamorphic Facies.***

Minerals indicative of these facies include analcite, stilbite, wairakite, pyrophyllite, cordierite, andalusite, sillimanite, K-feldspar, orthopyroxene, sanidine, and mullite. In mafic/ultramafic rocks, albite, actinolite, epidote, hornblende, pyroxenes and olivine my occur . In carbonate rocks, minerals such as talc, tremolite, diopside, forsterite, grossularite, wollastonite, and spurrite may develop.

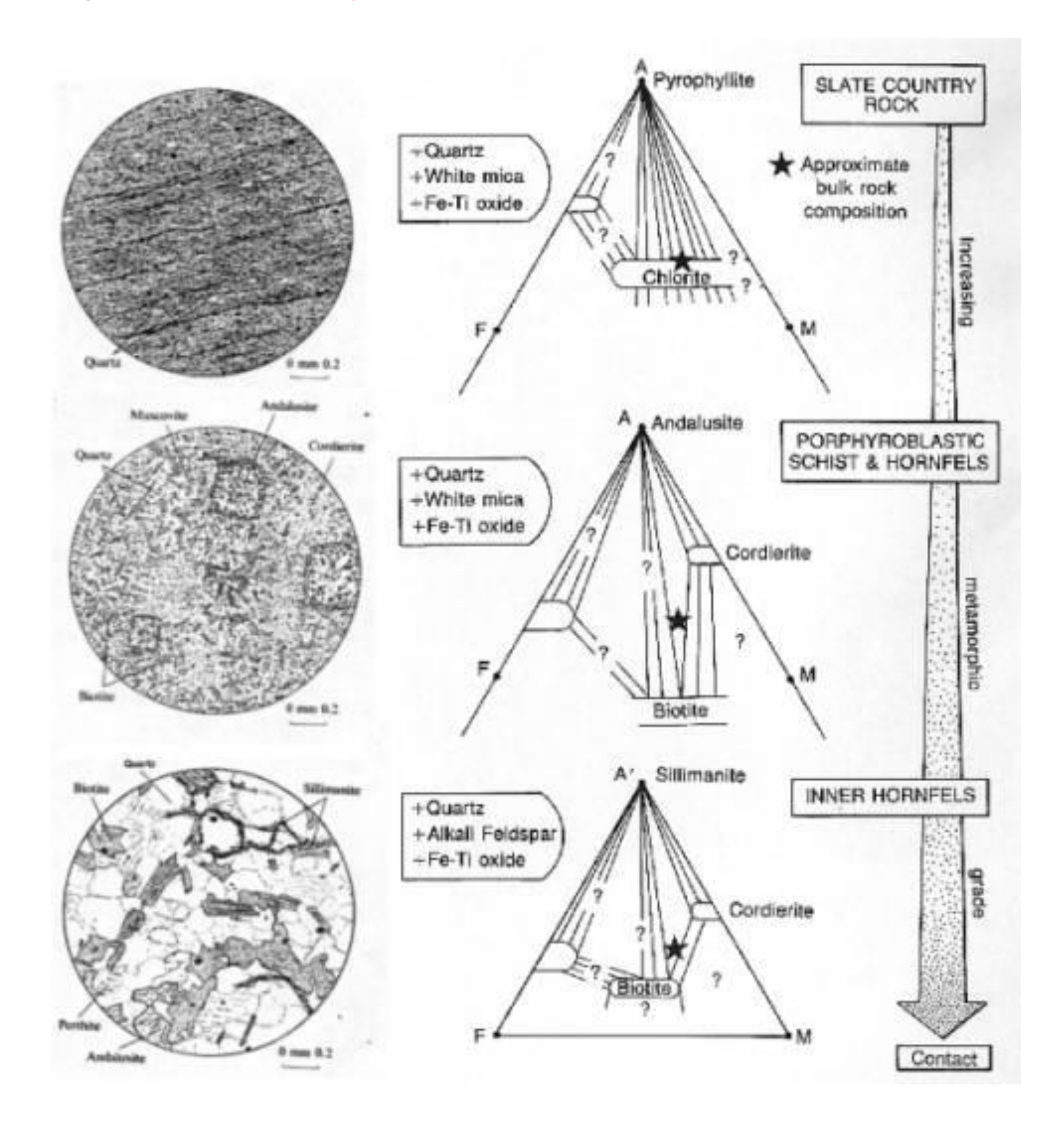


A classic example of a partial Contact Facies Series is provided by the contact aureole of the Devonian Onawa pluton of Maine (see figure to right). The granitic pluton was intruded into slate country rock previously metamorphosed under regional



metamorphic conditions. The country rocks contain the assemblage Fe-Ti oxide + white mica + chlorite + quartz (figure below). The first evidence of contact metamorphism is the appearance of spots in the slates as far as 2 km from the pluton margin. The spots are cordierite porphyroblasts (largely replaced by phyllosilicates) and are part of the assemblage biotite + andalusite + cordierite + white mica + quartz + albite. This assemblage is representative of the **Hornblende Hornfels Facies.**

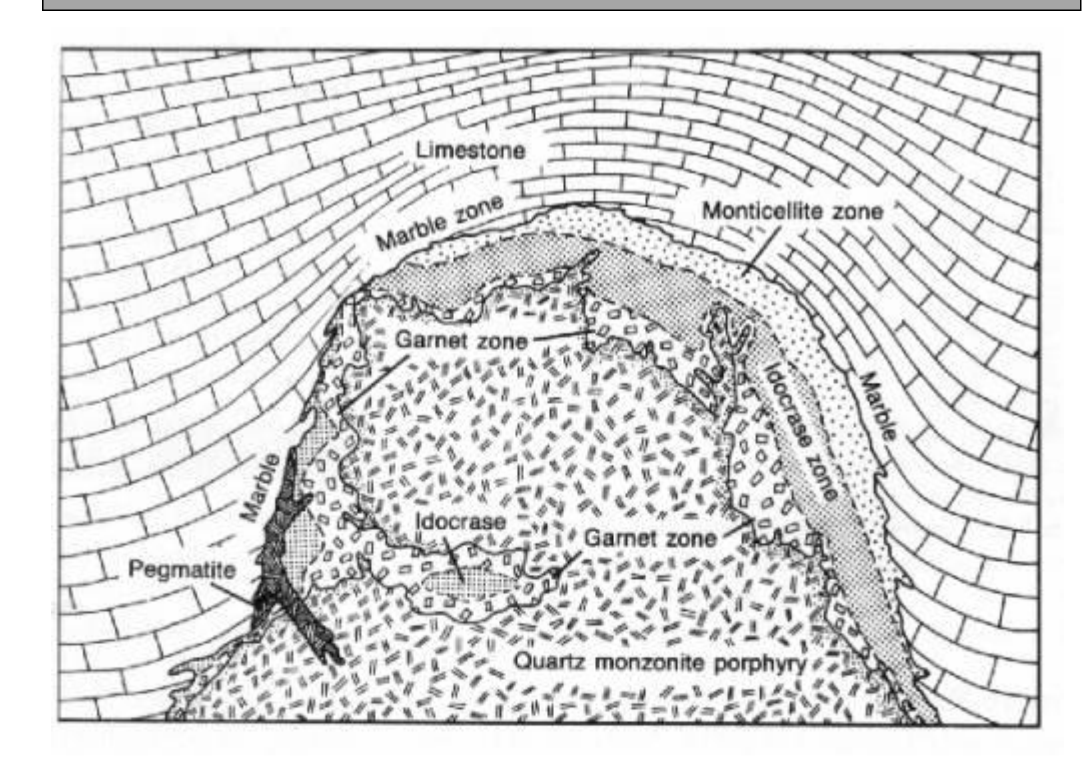
This outer zone surrounds an inner zone, adjacent to the pluton, composed of the assemblage biotite + sillimanite + cordierite + alkali feldspar + quartz. This assemblage is indicative **the Pyroxene Hornfels Facies.**



Conditions:

The conditions of contact metamorphism are those of low to moderate pressure and low to high temperature. Pressures are generally less than 4 kilobars. Temperatures of metamorphism vary widely from 400-1000°C. Among the controlling factors are:

1. the temperature of the magma.
2. the temperature of the country rock at the time of intrusion.
3. the conductivities of the solidifying magma and the country rock.
4. the diffusivity (of both the country rock and the intrusion).
5. the heat of crystallization of the magma.
6. the heat capacity (the rate of change in the energy of reaction with change in temperature).
7. fluid transport, the heating or cooling by influx of water.
8. contributions from other sources, such as radioactive.



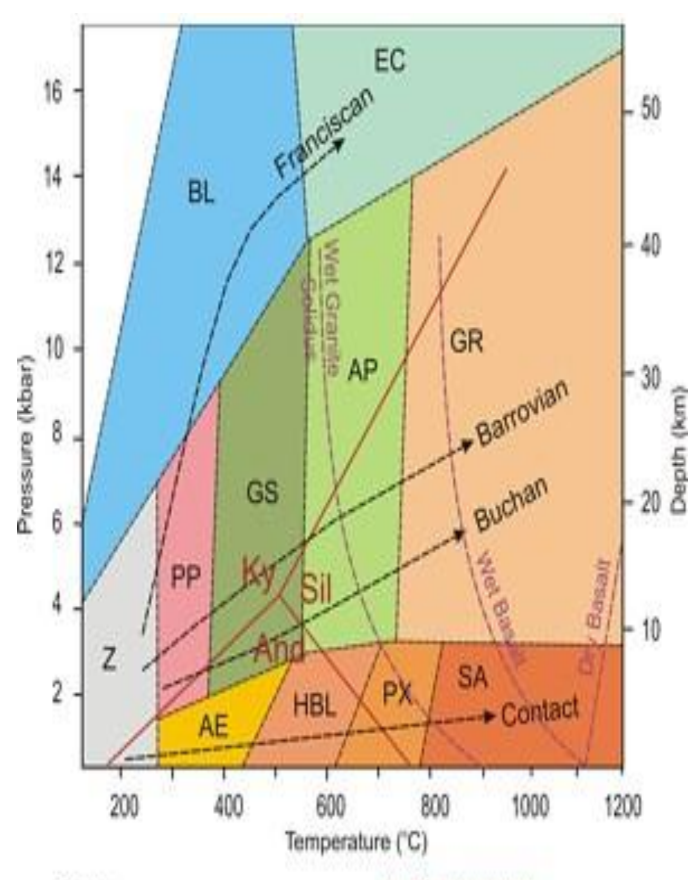
Now let's consider the metamorphic aureole at Crestmore, California (figure to the left). Quartz diorite and quartz monzonite have intruded a relatively pure limestone. The igneous rocks are surrounded by an aureole of variable width (< 3 cm-> 15 m) consisting of four parts. The outermost zone, referred to as the ***marble* zone**, consists of calcite marble and brucite-calcite marble. The marble zone is succeeded inwardly by the ***monticellite zone***, consisting of rocks composed of calcite and monticellite in association with one or more of the various minerals clinohumite, forsterite, melilite, spurrite, tilleyite, and merwinite. **An *idocrase zone*** occurs interior to the monticellite zone. The idocrase zone contains rocks composed of idocrase in association with such minerals as calcite, diopside, wollastonite, phlogopite, monticellite, and xanthophyllite. Closest to the intrusion is **the *garnet zone,*** where diopside-wollastonite-grossularite rocks, containing minor calcite and quartz, occur .

Examination of the key minerals indicates that metasomatism has occurred. The progressive sequence of key minerals and their chemistries is as follows:

calcite	$CaCO_3$
calcite + brucite	$CaCO_3 + Mg(OH)_2$
monticellite	$CaMgSiO_4$
idocrase	$Ca_{10}Mg_2Al_4Si_9O_{34}(OH)_4$
grossularite - wollastonite - diopside	$Ca_3Al_2Si_3O_{12}$ - $CaSiO_3$- $CaMgSi_2O_6$

Notice that there is a progressive increase in the ratio Si/Ca towards the contact with the intrusive and a similar increase in Al. Chemical analyses of the rocks confirm these trends and also indicate a slight enrichment in Fe^{3+}. As the original rock was a Mg-bearing limestone, the first two assemblages shown in the table indicate isochemical (no change in the chemistry) metamorphism. The latter three suggest an introduction of silica and alumina, or metasomatism.

Hornblende Hornfels Facies



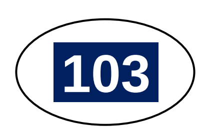
Hornblende hornfels facies is a medium-grade metamorphic facies associated with contact metamorphism at low pressures and moderate temperatures. Hornblende hornfels facies metamorphism occurs at temperatures of approximately 500 to 650 degrees celsius and at low (upper crust) pressures.

Changes in mineralogy depends very much on protolith. The absence of epidote, chlorite and albite distinguishes these rocks from those of **the albite epidote facies**, the presence of hornblend, and of muscovite in pelites distinguishes pelites from **the pyroxene hornfels facies.** In pelites biotite, cordierite and andalusite can occur as porphyroblasts, often rich in inclusions, however, these minerals are not restricted to this facies. Typical assemblages for different protoliths include:

mafic - hornblende/tremolite + plagioclase + biotite + cordierite + anthophyllite +/- quartz +/- almandine garnet.

pelites - hornblende/tremolite + quartz + plagioclase + muscovite + biotite +/- andalusite +/- cordierite.

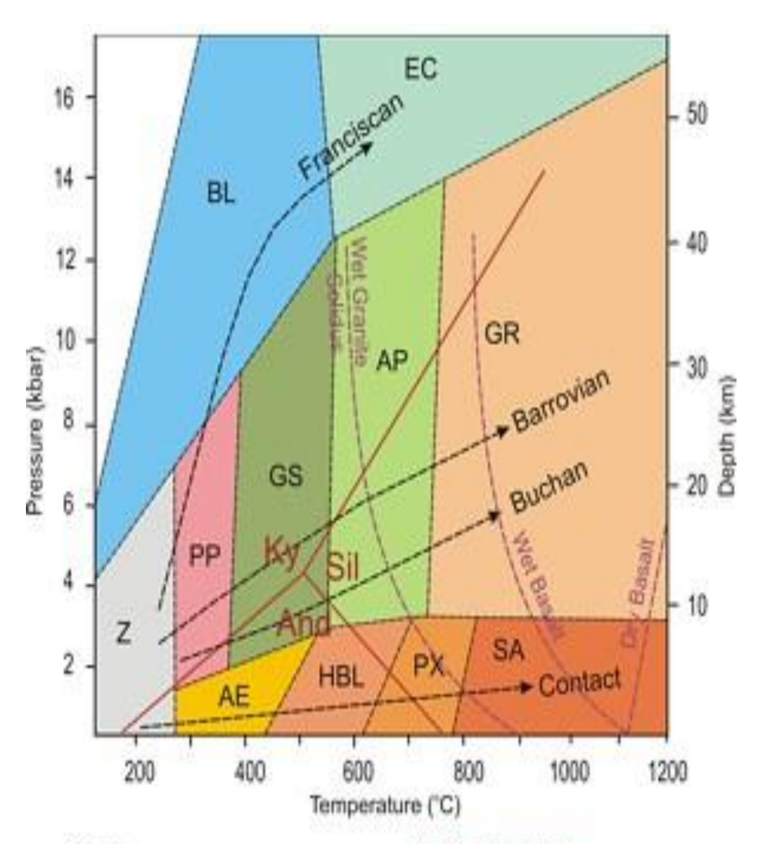
quartz-feldspathic - microcline + quartz +/- biotite +/- muscovite +/- almandine garnet.



calc-silicate - highly variable: calcite + plagioclase + tremolite + grossular garnet +/- diopside +/- quartz.

Like other contact metamorphic rocks, hornblende hornfels facies rocks can contain a wide range of minerals due to hydrothermal alteration to a skarn. Hornblende hornfels facies rocks trend towards equigranular fine-grained hornfels with granoblastic textures, however, porphyroblasts do occur.

Pyroxene Hornfels Facies



Facies
Z - zeolite facies
PP - pumpellyite prehnite facies
GS - greenschist facies
AP - amphibolite facies
GR - granulite facies
BL - blueschist facies
EC - eclogite facies
AE - albite epidote hornfels facies
HBL - hornblende hornfels facies
PX - pyroxene hornfels facies
SA - sanidinite facies

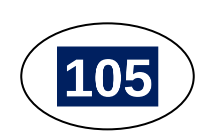
Al_2O_5 polymorphs
Ky - kyanite
And - andalusite
Sil - sillimanite

Pyroxene hornfels facies is a high-grade metamorphic facies associated with contact metamorphism at low pressures and high temperatures. Rocks of these facies often form the innermost zone of thermal aureoles. Pyroxene hornfels facies metamorphism occurs at temperatures of approximately 650 to 800 degrees celsius and at low (upper crust) pressures.

Changes in mineralogy depends very much on protolith. The absence of muscovite and hornblende and the presence of pyroxene in mafic rocks and sometimes in pelites distinguishes pelites from the hornblende hornfels facies. **In pelites** biotite, cordierite and andalusite or sillimanite can occur as porphyroblasts, often rich in inclusions. Typical assemblages for different protoliths include:

mafic - plagioclase + biotite + cordierite + orthopyroxene +/- quartz +/- diopside.

pelites - quartz + plagioclase + microcline + andalusite or sillimanite +/- cordierite.



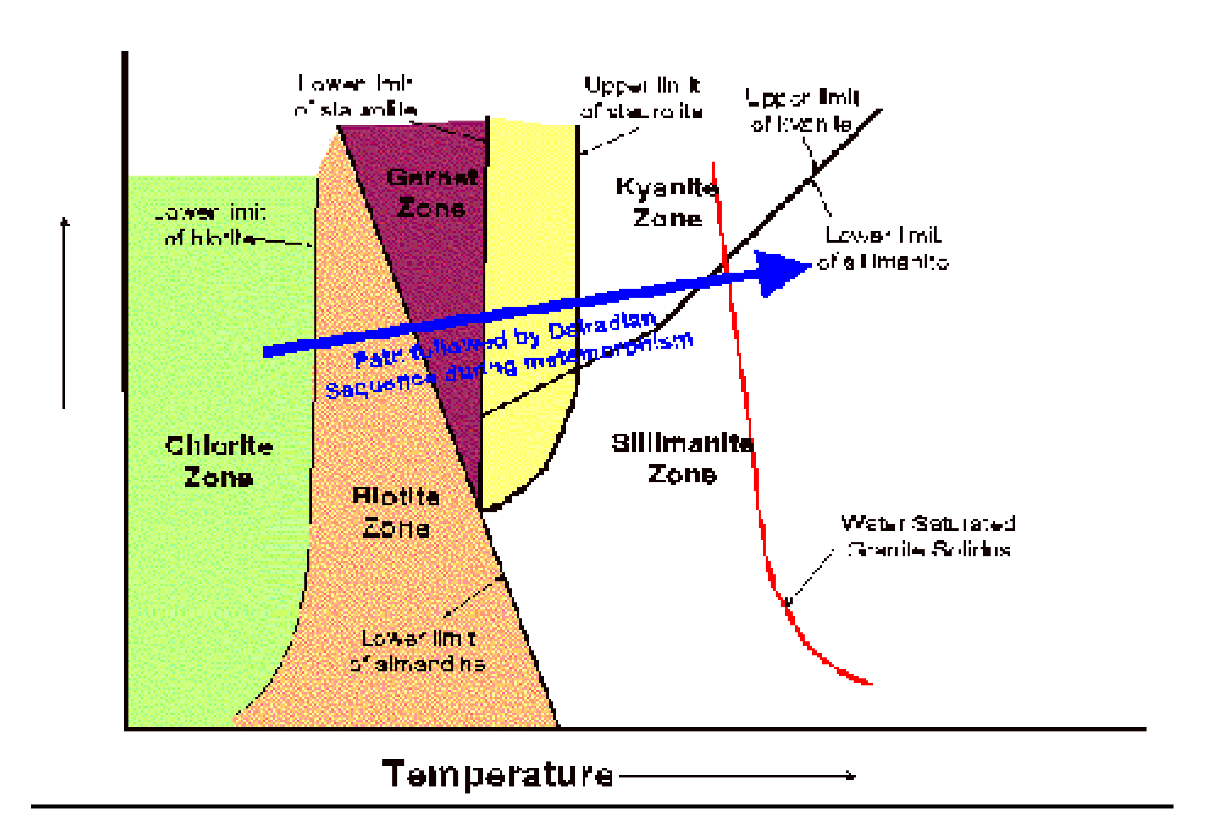
quartz-feldspathic - microcline + quartz +/- biotite +/- plagioclase.

calc-silicate - highly variable: calcite + plagioclase + grossular garnet +/- diopside +/- quartz +/- wollastonite.

Like other contact metamorphic rocks, pyroxene hornfels facies rocks can contain a wide range of minerals due to hydrothermal alteration to a skarn. Partial melting may occur in pyroxene hornfels facies rocks in the presence of water generated by dehydration reactions. Pyroxene hornfels facies rocks trend towards equigranular fine-grained hornfels with granoblastic textures, however, porphyroblasts do occur.

Metamorphic Zones and Facies:

Metamorphic Zones:



Metamorphic grade:

The degree of metamorphic recrystallization can range from almost no change to the protolith to changes that make the protolith unrecognizable, from the growth of new minerals in a shale to complete recrystallization as schist or gneiss. This variation in metamorphic grade is due to variations in the temperature and pressure (burial depth) that the protoliths experienced.

Barrovian metamorphic zones and index minerals:

late 19th century geologist were aware that specific metamorphic minerals formed at or above certain temperatures and pressure they could be used as index minerals for temperature and burial depth.

Barrows (1912) and Tilley (1925) mapped regional metamorphic rocks in Scotland based on the first appearance of several index materials from lowest to highest grade in pelitic (mud-rock) protoliths.

Chlorite zone lowest grade:

Rocks: chlorite-bearing slate, phyllite, schist.

Minerals: chlorite, sericite (phyllosilicate), muscovite quartz, albite (Na plag.) and pyrophyllite (phyllosilicate).

Biotite zone:

Growth of biotite mica, chlorite mica unstable.

Rocks: biotite-bearing phyllite and schist.

Minerals: remnant chlorite, muscovite, sericite, quartz, Na-rich plagioclase.

Garnet zone:

Growth of almandine (red, Fe-garnet).

Rocks: garnet-mica schist.

Minerals: almandine, biotite, muscovite, magnetite, quartz, Na-rich plagioclase.

Staurolite zone:

Growth of staurolite (nesosilicate related to kyanite & silimanite)

Rocks: staurolite-mica schist, staurolite-garnet-mica schist.

Minerals: staurolite, biotite, muscovite, almandine, quartz, k-spar.

Kyanite zone:

Growth of kyanite (Al_2SiO_5), staurolite not stable.

Rocks: kaynite schist, kyanite-mica schist.

Minerals: kyanite, biotite, muscovite, almandine, quartz, cordierite.

Silimanite zone:

Growth of silimanite (Al_2SiO_5), kyanite not stable.

Barrows & Tilley□s highest temperature zone:

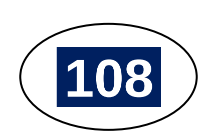
Rocks: silimanite schist, silimanite gneiss, cordierite gneiss.

Minerals: silimanite, biotite, muscovite, almandine, quartz, oligoclase and orthoclase feldspars, cordierite (cyclosilicate related to emerald & tourmaline).

Migmatites:

At even higher temperature, partial melting can begin in wet protoliths migmatites are an intermingling of gneissic banding and felsic igneous layers with increasing grade (temp & pressure) low-temperature, hydrous phyllosilicates are replaced by minerals stable at higher temp & pressure.

a problem with Barrovian metamorphic zones is that they were defined based on single index minerals that form from only one kind of protolithMetamorphic Facies .



Eskola (1920, 1939), Turner (1958) developed the concept of metamorphic facies based rock based on assemblages of minerals that should form together in a metamorphic on specific protoliths and at particular temperatures & pressures

Hornfels facies:

- high temp low pressure metamorphism

the product of contact metamorphism
most common in the upper crust (< 8-10 km) where the country rocks are relatively "cold" compared to the intruding magma
albite-epidote hornfels facies
< 450 °C contact metamorphism at < 6 km depth
meta Rx of this facies contain albite (Na-plag) and/or epidote (a hydrous sorosilicate) regardless of protolith.
includes other hydrous minerals, e.g., chlorite & actinolite.

Hornblende hornfels facies:

450-600 °C contact metamorphism at < 8 km depth
meta Rx of this facies contain hornblende and/or another amphibole (all hydrous) regardless of protolith.

Pyroxene hornfels facie:

600-800 °C contact metamorphism at < 8 km depth
found in direct contact with high temp, mafic intrusions
these Rx contain one or more pyroxenes (hypersthene, diopside, augite, enstatite) regardless of prototype
biotite is the only hydrous mineral in these high temperature metamorphic rocks.

Sanidinite hornfels facies:

> 800 °C contact metamorphism at < 8 km depth
rare, found around mafic & ultramafic intrusions
sanidine is common where protolith was felsic silicate composition
hydrous minerals are absent
increasing temp & pressure facies
greenschist through granulite facies correspond approximately to Barrovian regional.

Metamorphic Rocks and Facies:

Blueschist:



Blueschist is a rock that forms by the metamorphism of basalt and rocks with similar composition at high pressures and low temperatures, approximately corresponding to a depth of 15 to 30 kilometers and 200 to ~500 degrees Celsius.

The blue color of the rock comes from the presence of the mineral glaucophane.

Blueschists are typically found within orogenic belts as terranes of lithology in faulted contact with greenschist or rarely eclogite facies rocks.

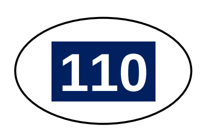
Petrology:

Blueschist as a rock type, is defined by the presence of the minerals glaucophane + (lawsonite or epidote) +/- jadeite +/- albite or chlorite +/- garnet +/- muscovite in a rock of roughly basaltic composition.

Blueschist often has a lepidoblastic, nematoblastic or schistose rock microstructure defined primarily by chlorite, phengitic white mica, glaucophane, and other minerals with an elongate or platy shape.

Grain size is rarely coarse, as mineral growth is retarded by the swiftness of the rock's metamorphic trajectory and perhaps more importantly, the low temperatures of metamorphism and in many cases the anhydrous state of the basalts.

However, coarse varieties do occur. Blueschists may appear blue, black, gray, or blue-green in outcrop. When lawsonite occurs in blueschists, it appears as white tabular crystals.



Blueschist facies:



garnet-lawsonite-glaucophane blueschist

Felsic rocks and pelitic sediments which are subjected to blueschist facies conditions will form different mineral assemblages than metamorphosed basalt.

Blueschist mineralogy varies by rock composition, but the classic equilibrium assemblages of blueschist facies are:

Basalts:

glaucophane + lawsonite and/or epidote + albite + titanite +/- garnet +/- quartz
jadeite + quartz - diagnostic of pressures ~> 10 kbar

Ultramafic rocks:

serpentine/lizardite +/- talc +/- zoisite

Pelites:

kyanite + zoisite +/- pargasite or phengite +/- albite +/- quartz +/- talc +/- garnet

Granites:

kyanite +/- paragonite +/- chlorite +/- albite +/- quartz +/- pargasite or phengite

Calc-silicates:

Limestones and marble: calcite transforms to aragonite at high pressure, but typically reverts to calcite when exhumed .Thus in order for blueschist facies assemblages to be seen at the Earth's surface, the rock must be exhumed swiftly enough to prevent total thermal equilibration of the rocks which are under blueschist facies conditions with the typical geothermal gradient.

Blueschists and other high-pressure subduction zone rocks are thought to be exhumed rapidly by flow and/or faulting in accretionary wedges or the upper parts of



subducted crust, or may return to the Earth's surface in part owing to buoyancy if the metabasaltic rocks are associated with low-density continental crust (marble, metapelite, and other rocks of continental margins).

Amphibolite:



Amphibolite is the name given to a rock consisting mainly of hornblende amphibole, the use of the term being restricted, however, to metamorphic rocks. The modern terminology for a holocrystalline plutonic igneous rocks composed primarily of hornblende amphibole is a hornblendite, which are usually crystal cumulates. Rocks with >90% amphibole which have a feldspar groundmass may be a lamprophyre.

Amphibolite is a grouping of rocks composed mainly of amphibole (as hornblende) and plagioclase feldspars, with little or no quartz. It is typically dark-colored and heavy, with a weakly foliated or schistose (flaky) structure. The small flakes of black and white in the rock often give it a salt-and-pepper appearance.

Amphibolites need not be derived from metamorphosed mafic rocks. Because metamorphism creates minerals based entirely upon the chemistry of the protolith, certain 'dirty marls' and volcanic sediments may actually metamorphose to an amphibolite assemblage. Deposits containing dolomite and siderite also readily yield amphibolites (tremolite-schists, grunerite-schists, and others) especially where there has been a certain amount of contact metamorphism by adjacent granitic masses. Metamorphosed basalts create ***ortho-amphibolites*** and other chemically appropriate lithologies create ***para-amphibolites***.

Tremolite, while it is a metamorphic amphibole, is derived most usually from highly metamorphosed ultramafic rocks, and thus tremolite-talc schists are not generally considered as 'amphibolites', because it is abundantly clear that one could just as easily say 'ultramafic schist'.

Because hornblende, as a mineral, is essentially a mineralogical 'garbage bin' and is stable across a very wide range of compositions and chemistries, as well as temperature and pressure conditions, it is suggested that the reader make use of the entries on amphibole chemistry.

Ortho-amphibolites vs. para-amphibolites:

Metamorphic rocks composed primarily of amphibole, albite, with subordinate epidote, zoisite, chlorite, quartz, sphene, and accessory leucoxene, ilmenite and magnetite which have a protolith of an igneous rock are known as ***Orthoamphibolites*****.**

Para-amphibolites will generally have the same equilibrium mineral assemblage as orthoamphibolites, with more biotite, and may include more quartz, albite, and depending on the protolith, more calcite/aragonite and wollastonite.

Often the easiest way to determine the true nature of an amphibolite is to inspect its field relationships; especially whether it is interfingered with other sediments, especially greywackes and other poorly sorted sediments. If the amphibolite appears to transgress apparent protolith bedding surfaces it is an ortho-amphibolite, as this suggests it was a dyke. Picking a sill and thin metamorphosed lava flows may be more troublesome.

Thereafter, whole rock geochemistry will suitably identify ortho- from para-amphibolites.

The word *metabasalt* was thus coined, largely to avoid the confusion between ortho-amphibolites and para-amphibolites. While not a true metamorphic rock name, as it infers an origin, it is a useful term.

Amphibolite Facies:

Amphibolites define a particular set of temperature and pressure conditions known as **the *amphibolite facies***. However, caution must be applied here before embarking on metamorphic mapping based on amphibolites alone.

Firstly, for an **(ortho)amphibolite** to be classed as a metamorphic amphibolite, it must be certain that the amphibole in the rock is a prograde metamorphic product, and not a retrograde metamorphic product. For instance, **actinolite amphibole** is a common product **of retrograde metamorphism** of basalts at (upper) greenschist facies conditions. Often, this will take on the crystal form and habit of the original protolith assemblage; actinolite pseudomorphically replacing pyroxene is an indication that the amphibolite may not represent a peak metamorphic grade in the amphibolite facies. **Actinolite schists** are often the result of hydrothermal alteration or metasomatism, and thus may not, necessarily, be a good indicator of metamorphic conditions when taken in isolation.

Secondly, the microstructure and crystal size of the rock must be appropriate. Amphibolite facies conditions are experienced at temperatures in excess of 500 °C and pressures in excess of 1.2 GPa, well within the ductile deformation field. Gneissic

Granulite:



Granulites are fine to medium–grained metamorphic rocks that have experienced high temperatures of metamorphism, composed mainly of feldspars sometimes associated with quartz and anhydrous ferromagnesian minerals, with granoblastic texture and gneissose to massive structure.

They are of particular interest to geologists because many granulites represent samples of the deep continental crust. Some granulites experienced decompression from deep in the Earth to shallower crustal levels at high temperature; others cooled while remaining at depth in the Earth.

The minerals present in a granulite will vary depending on the parent rock of the granulite and the temperature and pressure conditions experienced during metamorphism.

A common type of granulite found in high-grade metamorphic rocks of the continents contains pyroxene, plagioclase feldspar and accessory garnet, oxides and possibly amphibole.

Both clinopyroxene and orthopyroxene may be present, and in fact, the coexistence of clino- and orthopyroxene in a metamorphosed basalt defines the Granulite facies.

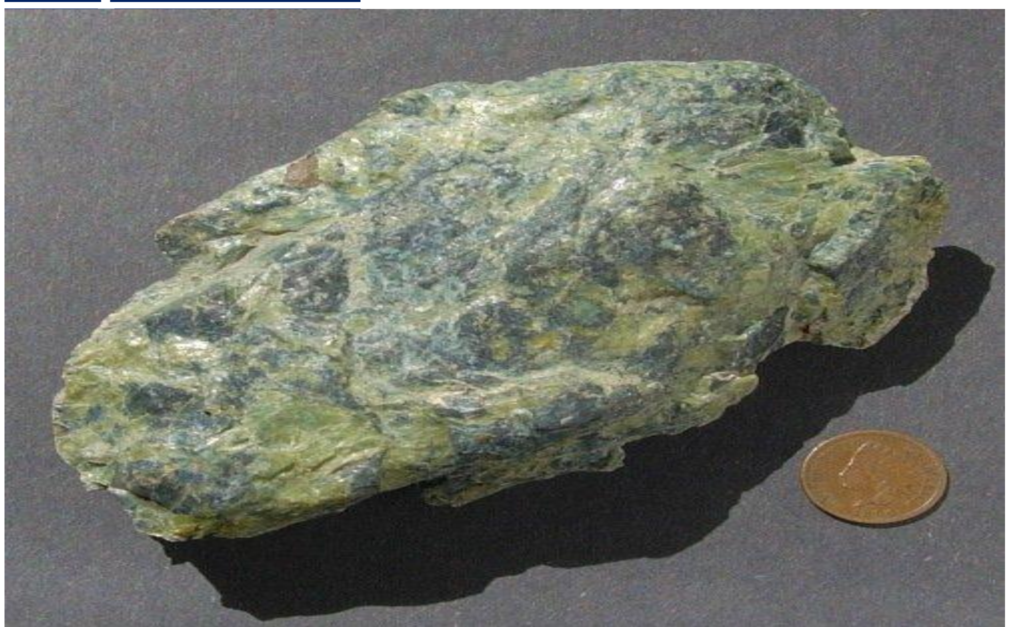
Formation:

Granulites form at high temperature conditions at a range of pressure conditions, typically during regional metamorphism.

In some cases, the high temperatures are difficult to account for at the inferred depths at typical geothermal gradients. In extreme cases, granulites may form at temperatures in excess of 1000 degrees Celsius. Some granulites may represent the residues of partial melting, and in other cases represent rocks that never melted, despite extremely high temperatures, because the minerals are anhydrous and therefore do not melt even at high temperature conditions.

In continental crustal rocks, biotite may break down at high temperatures to form orthopyroxene + potassium feldspar + water, producing a granulite. Other possible minerals formed at dry conditions include sapphirine, spinel, sillimanite, and osumilite. Some assemblages such as sapphirine + quartz indicate very high temperatures.

Serpentinite:



Serpentinite is a rock composed of one or more serpentine minerals. Minerals in this group are formed by **serpentinization**, a hydration and metamorphic transformation of ultramafic rock from the Earth's mantle. The alteration is particularly important at the sea floor at tectonic plate boundaries. It is the state rock of California, USA although the California Legislature specified that serpentine was "the official State Rock and lithologic emblem.

Formation:

Serpentinization is a geological low-temperature metamorphic process involving heat and water in which low-silica mafic and ultramafic rocks are oxidized and hydrolyzed with water into serpentinite. Peridotite, including dunite, at and near the seafloor and in mountain belts is converted to serpentine, brucite, magnetite, and other minerals -- some rare, such as awaruite (Ni_3Fe), and even native iron. In the process large amounts of water are absorbed into the rock increasing the volume and destroying the structure.

The density changes from 3.3 to 2.7 g/cm^3 with a concurrent volume increase of about 40%. The reaction is exothermic and large amounts of heat energy are produced in the process.

Rock temperatures can be raised by about 260 ^oC, providing an energy source for formation of non-volcanic hydrothermal vents. The magnetite-forming chemical reactions produce hydrogen gas. Carbonates and sulfates are reduced and form methane and hydrogen sulfide. The hydrogen, methane, and hydrogen sulfide provide energy sources for deep sea chemotroph microorganisms.

Serpentinite reactions:

Serpentinite is formed from olivine via several reactions, some of which are complementary. **Olivine** is a solid solution between the magnesium-endmember forsterite and the iron-endmember fayalite. Serpentinite reactions 1a and 1b, below, exchange silica between forsterite and fayalite to form serpentine-group minerals and magnetite. These are highly exothermic reactions.

Reaction 1a:
Fayalite + water → Magnetite + aqueous silica + hydrogen

$$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$$

Reaction 1b:
Forsterite + aqueous silica → Serpentine

$$3Mg_2SiO_4 + SiO_2 + 4H_2O \rightarrow 2Mg_3Si_2O_5(OH)_4$$

Other possibilities include the reaction of olivine plus water to yield serpentine plus $Mg(OH)_2$ (brucite), and reactions in which magnesium and silica are transported out of the serpentinizing volume.

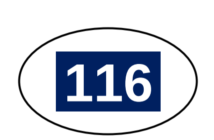
A similar suite of reactions involves pyroxene-group minerals, though less readily and with complication of the additional end-products due to the wider compositions of pyroxene and pyroxene-olivine mixes. Talc and magnesian chlorite are possible products, together with the serpentine minerals antigorite, lizardite, and chrysotile. The final mineralogy depends both on rock and fluid compositions, temperature, and pressure. Antigorite forms in reactions at temperatures that can exceeed 600°C during metamorphism, and it is the serpentine-group mineral stable at the highest temperatures. Lizardite and chrysotile can form at low temperatures very near the Earth's surface. Fluids involved in serpentinite formation commonly are highly reactive and may transport calcium and other elements into surrounding rocks; fluid reaction with these rocks may create metasomatic reaction zones enriched in calcium and called rodingites.

In the presence of carbon dioxide, however, serpentinitization may form either magnesite ($MgCO_3$) or generate methane (CH_4). It is thought that some hydrocarbon gases may be produced by serpentinite reactions within the oceanic crust, and the serpentinite reaction is a key argument for the theory of abiogenic petroleum origin.

Reaction 2a:

Olivine + Water + Carbonic acid → Serpentine + Magnetite + Methane

$$(Fe, Mg)_2SiO_4 + nH_2O + CO_2 \rightarrow Mg_3Si_2O_5(OH)_4 + Fe_3O_4 + CH_4$$



or, in balanced form: $18Mg_2SiO_4 + 6Fe_2SiO_4 + 26H_2O + CO_2 \rightarrow 12Mg_3Si_2O_5(OH)_4 + 4Fe_3O_4 + CH_4$

Reaction 2b:

Olivine + Water + Carbonic acid → Serpentine + Magnetite + Magnesite + Silica

Reaction 2a is favored if the serpentinite is Mg-poor or if there isn't enough carbon dioxide to promote talc formation. Reaction 2b is favored in highly magnesian compositions and low partial pressure of carbon dioxide. (Something is missing from Reaction 2b because Fe is oxidized and nothing gets reduced.)

The degree to which a mass of ultramafic rock undergoes serpentinisation depends on the starting rock composition and on whether or not fluids transport calcium, magnesium and other elements away during the process. If an olivine composition contains sufficient fayalite, then olivine plus water can completely metamorphose to serpentine and magnetite in a closed system. In most ultramafic rocks formed in the Earth's mantle, however, the olivine is about 90% forsterite endmember, and for that olivine to react completely to serpentine, magnesium must be transported out of the reacting volume.

Serpentinitization of a mass of peridotite usually destroys all previous textural evidence because the serpentine minerals are weak and behave in a very ductile fashion. However, some masses of serpentinite are less severely deformed, as evidenced by the apparent preservation of textures inherited from the peridotite, and the serpentinites may have behaved in a rigid fashion.

Eclogite:



Eclogite piece with a garnet (red) and omphacite (greyish-green) groundmass. The sky-blue crystals are kyanite. Some white quartz is seen too, it was probably once



coesite. A few gold-white phengite mica minerals can be seen at the top. Coin of 1 euro (2,3 cm) for scale.



Eclogite is a coarse-grained mafic (basaltic in composition) metamorphic rock. Eclogite is of special interest for at least two reasons. First, it forms at pressures greater than those typical of the crust of the Earth.

Second, being unusually dense rock, eclogite can play an important role in driving convection within the solid Earth.

The fresh rock can be striking in appearance, with red to pink garnet (almandine-pyrope) in a green matrix of sodium-rich pyroxene (omphacite).

Accessory minerals include kyanite, rutile, quartz, lawsonite, coesite, amphibole, phengite, paragonite, zoisite, dolomite, corundum, and, rarely, diamond.

Plagioclase is not stable in eclogites. Glaucophane and titanite (sphene) form in eclogite as pressures decrease during exhumation of the rocks, or may be earlier formed minerals that did not entirely react away.

Origins:

Eclogite typically results from high-pressure metamorphism of mafic igneous rock (typically basalt or gabbro) as it plunges into the mantle in a subduction zone.

Such eclogites are generally formed from precursor mineral assemblages typical of blueschist metamorphism.

Eclogite can also form from magmas that crystallize and cool within the mantle or lower crust of continents.

Eclogite facies:

Eclogite facies is determined by the temperature and pressure conditions required to metamorphose basaltic rocks to an eclogite assemblage.

The typical eclogite mineral assemblage is garnet (pyrope to almandine) plus clinopyroxene (omphacite).



This is extremely high pressure, medium to high temperature metamorphism.

Eclogites containing lawsonite (a hydrous calcium-aluminium silicate) are very rarely exposed at the Earth's surface, although they are predicted from experiments to form during normal subduction of oceanic crust at depths between ~ 45-300 kilometers..

Eclogite is the highest pressure metamorphic facies and is usually only the result of advancement from blueschist metamorphic conditions.

Importance of eclogite:



Eclogite is a rare and important rock because it is formed only by conditions typically found in the mantle or the lowermost part of thickened continental crust.

Eclogites are helpful in elucidating patterns and processes of plate tectonics because many represent oceanic crust that has been subducted to depths in excess of 35 km and then returned to the surface.

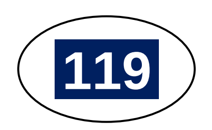
Eclogite that is brought to shallow conditions is unstable, and retrograde metamorphism often occurs: secondary amphibole and plagioclase may form reaction rims on the primary pyroxene, and titanite may form rims about rutile.

, then it would melt by decompression melting (see discussion in igneous rock) at lower temperature than the accompanying peridotite. Eclogite-derived melts may therefore be part of the melt contribution derived from mantle plumes.



Gneiss:





Gneiss is a common and widely distributed type of rock formed by high-grade regional metamorphic processes from pre-existing formations that were originally either igneous or sedimentary rocks.

Gneissic rocks are usually medium to coarse foliated and largely recrystallized but do not carry large quantities of micas, chlorite or other platy minerals.

Gneisses that are metamorphosed igneous rocks or their equivalent are termed granite gneisses, diorite gneisses, etc. However, depending on their composition, they may also be called garnet gneiss, biotite gneiss, albite gneiss, etc.

Orthogneiss designates a gneiss derived from an igneous rock, and ***paragneiss*** is one from a sedimentary rock. *Gneissose* is used to describe rocks with properties similar to gneiss.

Gneiss resembles schist, except that the minerals are arranged into bands. Sometimes it is difficult to tell the difference between gneiss and a schist because some gneiss appears to have more mica than it really does. This is especially true with mica-rich parting planes.

Augen gneiss:



Augen gneiss is a coarse-grained gneiss, interpreted as resulting from metamorphism of granite, which contains characteristic elliptic or lenticular shear bound feldspar porphyroclasts, normally microcline, within the layering of the quartz, biotite and magnetite bands.

Schist:



The schists form a group of medium-grade metamorphic rocks, chiefly notable for the preponderance of lamellar minerals such as micas, chlorite, talc, hornblende, graphite, and others.

Quartz often occurs in drawn-out grains to such an extent that a particular form called quartz schist is produced. By definition, schist contains more than 50% platy and elongated minerals, often finely interleaved with quartz and feldspar.
The individual mineral grains in schist, drawn out into flaky scales by heat and pressure, can be seen by the naked eye. Schist is characteristically *foliated*, meaning the individual mineral grains split off easily into flakes or slabs.

The word schist is derived from the Greek word *σχίζειν* meaning "to split", which is a reference to the ease with which schists can be split along the plane in which the platy minerals lie.

Most schists have been derived from clays and muds which have passed through a series of metamorphic processes involving the production of shales, slates and phyllites as intermediate steps.
Certain schists have been derived from fine-grained igneous rocks such as basalts and tuffs. Most schists are mica schists, but graphite and chlorite schists are also common. Schists are named for their prominent or perhaps unusual mineral constituents, such as garnet schist, tourmaline schist, glaucophane schist, etc.

Formation:



During metamorphism, rocks which were originally sedimentary or igneous are converted into schists and gneisses.

If the composition of the rocks was originally similar, they may be very difficult to distinguish from one another if the metamorphism has been great.

A quartz-porphyry, for example, and a fine grained feldspathic sandstone, may both be converted into a grey or pink mica-schist. Usually, however, it is possible to distinguish between sedimentary and igneous schists and gneisses.

If the whole district, for example, occupied by these rocks have traces of bedding, clastic structure, or unconformability then it may be a sign that the original rock was sedimentary.

In other cases intrusive junctions, chilled edges, contact alteration or porphyritic structure may prove that in its original condition a metamorphic gneiss was an igneous rock.

The last appeal is often to the chemistry, for there are certain rock types which occur only as sediments, while others are found only among igneous masses, and however advanced the metamorphism may be, it rarely modifies the chemical composition of the mass very greatly. Such rocks, for example, as limestones, dolomites, quartzites and aluminous shales have very definite chemical characters which distinguish them even when completely recrystallized.



The schists are classified principally according to the minerals they consist of and on their chemical composition. For example, many metamorphic limestones, marbles, and calc-schists, with crystalline dolomites, contain silicate minerals such as mica, tremolite, diopside, scapolite, quartz and feldspar.

They are derived from calcareous sediments of different degrees of purity. Another group is rich in quartz (quartzites, quartz schists and quartzose gneisses), with variable amounts of white and black mica, garnet, feldspar, zoisite and hornblende. These were once sandstones and arenaceous rocks.

The graphitic schists may readily be believed to represent sediments once containing coal or plant remains; there are also schistose ironstones (hematite-schists), but metamorphic beds of salt or gypsum are exceedingly uncommon.



Among schists of igneous origin there are the silky calc-schists, the foliated serpentines (once ultramafic masses rich in olivine), and the white mica-schists, porphyroids and banded halleflintas, which have been derived from rhyolites, quartz-porphyries and felsic tuffs. The majority of mica-schists, however, are altered claystones and shales, and pass into the normal sedimentary rocks through various types of phyllite and mica-slates. They are among the most common metamorphic rocks; some of them are graphitic and others calcareous. The diversity in appearance and composition is very great, but they form a well-defined group not difficult to recognize, from the abundance of black and white micas and their thin, foliated, schistose character.

As a special subgroup we have the andalusite, staurolite, kyanite and sillimanite-schists which usually make their appearance in the vicinity of gneissose granites, and have presumably been affected by contact metamorphism. The schist rock can be found worldwide and is popular for collectors.

Phyllite:



Phyllite is a type of foliated metamorphic rock primarily composed of quartz, sericite mica, and chlorite; the rock represents a gradation in the degree of metamorphism between slate and mica schist.

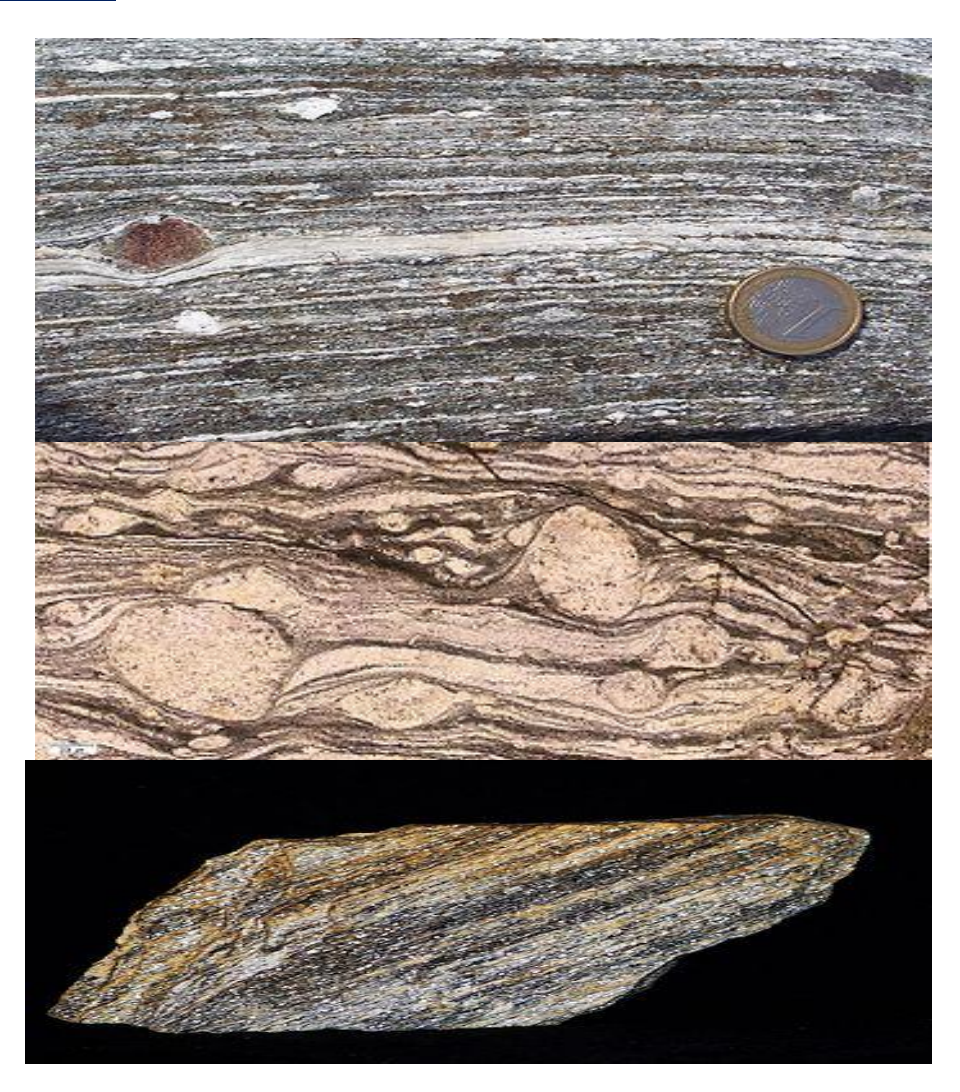
Minute crystals of graphite, sericite, or chlorite impart a silky, sometimes golden sheen to the surfaces of cleavage (or schistosity).

Phylite is formed from the continued metamorphism of slate.

The protolith (or parent rock) for a phyllite is a slate. Its constituent platy minerals are larger than those in slate but are not visible with the naked eye. Phyllites are said to have a "phyllitic texture" and are usually classified as having a low grade in the regional metamorphic facies.

Phyllite has a good fissility (a tendency to split into sheets) and will form under low grade metamorphic conditions. Phyllites are usually black or gray. The foliation is commonly crinkled or wavy in appearance.

Mylonite:



Mylonite is a fine-grained, compact rock produced by dynamic crystallization of the constituent minerals resulting in a reduction of the grain size of the rock. It is classified as a metamorphic rock.

Mylonites can have many different mineralogical compositions; it is a classification based on the textural appearance of the rock.

Formation:

Mylonite is a ductilely deformed rock formed by the accumulation of large shear strain, in ductile fault zones.



There are many different views on the formation of mylonite, but it is generally agreed that crystal-plastic deformation must have occurred, and that fracturing and cataclastic flow are secondary processes in the formation of mylonite.

Mechanical abrasion of grains by milling does not occur, although this was originally thought to be the process that formed mylonite, which was named from the Greek μύλος *mylos*, meaning mill.

There are many different mechanisms that accommodate crystal-plastic deformation. In crustal rocks the most important processes are dislocation creep and diffusive mass transfer.

Volume and surface diffusion are important ductile deformation mechanisms at high metamorphic grades, particularly if the grain size is small.

Dislocation glide and dislocation creep both act to increase the internal energy of crystals.

This effect is compensated through recrystallization which reduces the internal energy by increasing the surface area and reducing the volume, storing energy at the mineral grain surface.

Thus mylonites, which are characterized by small grain sizes relative to surrounding rocks, are interpreted to result from extensive ductile deformation.

Mylonites generally develop in ductile shear zones where high rates of strain are focused. They are the deep

counterparts to cataclastic brittle faults that create fault breccias.

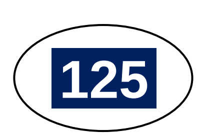
Classification:

- ***Blastomylonites*** are coarse grained, often sugary in appearance without distinct tectonic banding.
- ***Ultramylonites*** have undergone extreme grainsize reduction. They are hard, dark, cherty to flinty in appearance and may be confused with pseudotachylite and obsidian.
- ***Phyllonites*** are phyllosilicate(e.g. chlorite or mica)-rich mylonites. They typically have a well-developed secondary shear (C') fabric.

Interpretation:

Determining the displacements that occur in mylonite zones is dependent on correctly determining the orientations of the finite strain axis and inferring how they change their orientation with respect to the incremental strain axis.

This is referred to as determining the shear sense. It is common practice to assume that the deformation is a plane strain simple shear deformation.



This type of strain field assumes that deformation occurs in a tabular zone where displacement is parallel to the shear zone boundary.

Furthermore, during deformation the incremental strain axis maintains a 45 degree angle to the shear zone boundary. The finite strain axis are initially parallel to the incremental axis, but rotate away during progressive deformation.

Kinematic indicators are structures in mylonite that allow the sense of shear to be determined.

Most kinematic indicators are based on deformation in simple shear zones and infer sense of rotation of the finite strain axis with respect to the incremental strain axis.

Because of the constraints imposed by simple shear, displacement is assumed to occur in the foliation plane in a direction parallel to the mineral stretching lineation .

. Therefore a plane parallel to the lineation and perpendicular to the foliation is viewed to determine the shear sense.

The most common shear sense indicators are C/S fabrics, asymmetric porphyroclasts, vein and dike arrays, mantled porphyroclasts and mineral fibers.

All of these indicators have a monoclinic symmetry which is directly related to the orientations of the finite strain axis.

Although structures like asymmetric folds and boudins are also related to the orientations of the finite strain axis, these structures can form from distinct strain paths and are not reliable kinematic indicators .

سحنات التحول:
metamorphic facies

في محاولة لتحديد أنواع الصخور المتحولة التي تسود في نطاقات التحول المختلفة, فقد اخترع العالم اسكولا(1939) Escola مصطلح سحنات التحول metamorphic facies للتعبيرعن: مجموعة من الصخور المتحولة التي تتشابه في تجمعاتها المعدنية Mineral assemblage وتختلف في تراكيبها الكيميائية Chemical composition.

التجمع المعدني Mineral assemblage: عبارة عن مجموعة من المعادن المختلفة في صخر, تكون في حالة إتزان تحت ظروف معينة من الضغط والحرارة.

تسمى السحنة دائماً باسم احد أنواع الصخور الشائعة التي تنتمي للمجموعة مثل سحنة الشست الأخضرGreen schist facies و سحنة الامفيبولايت AMPHIBOLITE FACIES.

هنالك العديد من أنواع السحنات أهمها الآتي:

1) سحنة الزيولايت Zeolite facies

هي السحنة التي تسود نطاق التحول الاقليمى ذات درجات الحرارة العادية الواطئة (200 – 300) والضغط الواطئ 02000- 300 بار).

الصخور في هذه السحنة تعتبر نتاج عملية إنتقالية بين عملية التحويرDiagenesis وعملية التحول metamorphism والتي تتضمن تكوين معدن الزيولايت Zeolite والمعادن طينية وتبلور الكوارتز والفلسبار.

2) سحنة الشست الأخضرGreen schist facies

هي السحنة التي تسود نطاق التحول الاقليمى ذات درجات الحرارة العادية الواطئة والضغط المتوسط.

يتميز النطاق بوجود صخور الشست الأخضر Green schist والتي تتكون من معادن السيلكات المائية (غالباً معادن خضراء) مثل المسكوفايت Muscovite, الكلورايت Chlorite, التلك Talc, الأكتينولايت Actonolite, الأبيدوت Epidote والجلوكوفين Golocophane.

3) سحنة الامفيبولايت Amphibolite Facies

تدخل في نطاق التحول الاقليمي في ظروف من الحرارة المعتدلة والضغط المعتدل.

يتميز النطاق بوجود صخور الأمفيبولايت والشست schist ذات التراكيب الصفائحية Foliated والخطية Banded والغني بمعادن المسكوفايتMuscovite, البيوتايتBiotite,
الاشتارولايتStaourolite,الكياناتيKyanite, الهورنبلندHornblende, البلاجيوكليز Plagioclase والكالسايت Calcite

4) سحنة الجرانيولايت Granulite facies

نتاج تحول اقليمي في المناطق السحيقة ذات درجات الحرارة العالية جداً والضغط المنتظم العالي جداً.

يتميز النطاق بوجود صخورمتماسكة Crystalline ذات تبلور كيميائي وتشوه كبير والغني بمعادن قريبة من المعادن المتكونة مباشرة من الصهير مثل صخور النايس Gneiss والجرانيولايت Granulite والتي تحتوي غالباً علي معادن البلاجيوكليز Plagioclase, الهورنبلند Hornblende, البيوتايت Biotite, البيروكسين Pyroxene والقارنت Garnet.

5) سحنة البروكسين- هورنفلس Pyroxene-Hornefels facies

نتاج تحول تماسي حراري في مناطق تداخل الكتل الصهيرية في ظروف من الحرارة العالية جداً والضغط الاتجاهي المعتدل. يتم التحول في الأجزاء الداخلية من دائرة التحول بالقرب من مركز تداخل الكتل الصهيرية

6) سحنة الساندينايت Sanidinite facies

تدخل أيضاً في نطاق التحول الحراري التماسي في مناطق التي تتوفر فيها ظروف من الحرارة العالية جداً والضغط الواطئ (في السطح أو في اعماق ضحلة).

7) سحنة الأكلوجايت Eclogite facies

تسود المناطق السحيقة ذات درجات الحرارة العالية جداً والضغط المنتظم العالي جداً.

يتميز النطاق بوجود صخورمتماسكة Crystalline وغنية بمعادن الأمفوسايت Omphacite والبيروكسين Pyroxene .

CHAPTER 7

Common Types of Metamorphic rocks

Foliated (Layered) Metamorphic Rocks:

1. Slate:

Slate is a contact metamorphic rock, and the parent sedimentary rocks are mostly clays or shales. The main minerals include andalusite, biotite and muscovite. It is found worldwide, especially in Wales, Scotland, Norway, Finland, France and the Sierra Nevada, California. Slate is usually grey or black. It splits easily into thin sheets which are used for roofing and as flagstones. The name comes from an Old French word meaning to splinter. A low-grade metamorphic rock derived from regional metamorphism of shale. Microscopic grains are only visible under magnification. The rock can easily be split into thin sheets, hence its popular use as a roofing material. It is usually dark grey to black, but may sometimes be yellow, blue, green, red or brown. It is soft and can easily be scratched with a knife. Slate is metamorphosed shale. Slate is tougher than shale and it breaks into thin, flat layers. Slate is usually dark gray, but it can also be red colored. Slate has been used in some countries as roofing and more recently, it has been utilized as floor tiles**.**





2. Phyllite:

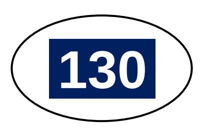
A metamorphic rock derived from shale but more metamorphosed than slate. The rock is frequently banded, micaceous, and has a coarser texture than slate. Silky luster due to mica grains. The rock is sometimes foliated with uniform composition, grading into schist.

Phyllite is metamorphosed slate.It is still foliated (layered), but unlike slate, the layers are not completely flat but have a slightly undulating pattern. Phyllite also has a slightly silky appearance due to the growth of tiny mica plates oriented parallel to the foliation.

Phyllite



Phyllite is a foliate metamorphic rock that is made up mainly of very fine-grained mica. The surface of phyllite is typically lustrous and sometimes wrinkled. It is intermediate in grade between slate and schist. The specimen shown above is about two inches (five centimeters across).



3. Schist:

A highly metamorphosed rock, more so than phyllite, generally formed by regional metamorphism. It can range in colour form light to dark and has a medium to coarse texture. Visible grains are often present but may be finer than gneiss. The rock typically breaks into a wavy surface along parallel foliated bands - a characteristic known as schistosity. The rock can form from igneous, sedimentary or other metamorphic rocks. Several varieties are known, named after the main mineral content. Hornblende Schist thus contains hornblende. Chlorite Schist (also known as greenstone) contains chlorite. Mica Schist typically contains biotite or muscovite and quartz. Its the most common type of schist. Sparkling luster can dull on weathering. The hardness and density vary according to different sources and mineral content present.

Schist is metamorphosed phyllite. The mica crystals in schists are larger than those in phyllites and so schists tend to distinctly sparkle. Mica schists often also contain garnet crystals or staurolite crystals, producing a bumpy surface. Schists might also be made of talc, kyanite, pyrophyllite, chlorite, or sillimanite .

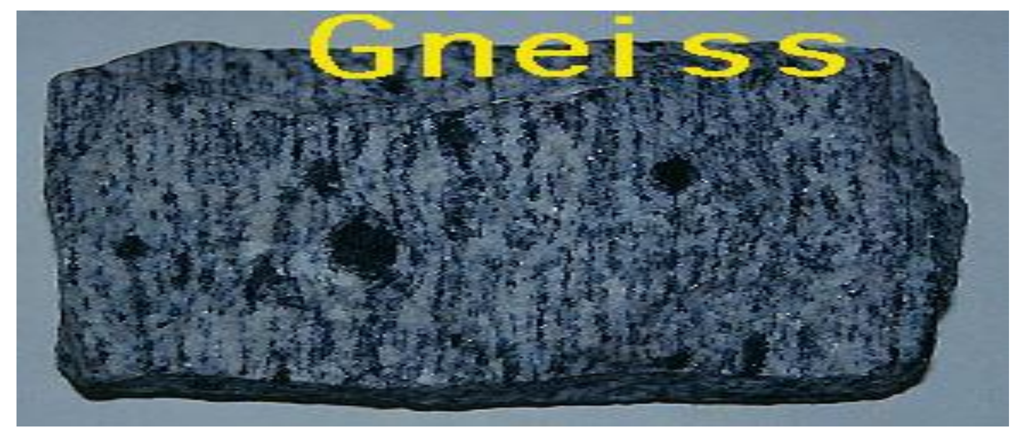



Schist (Muscovite Schist)



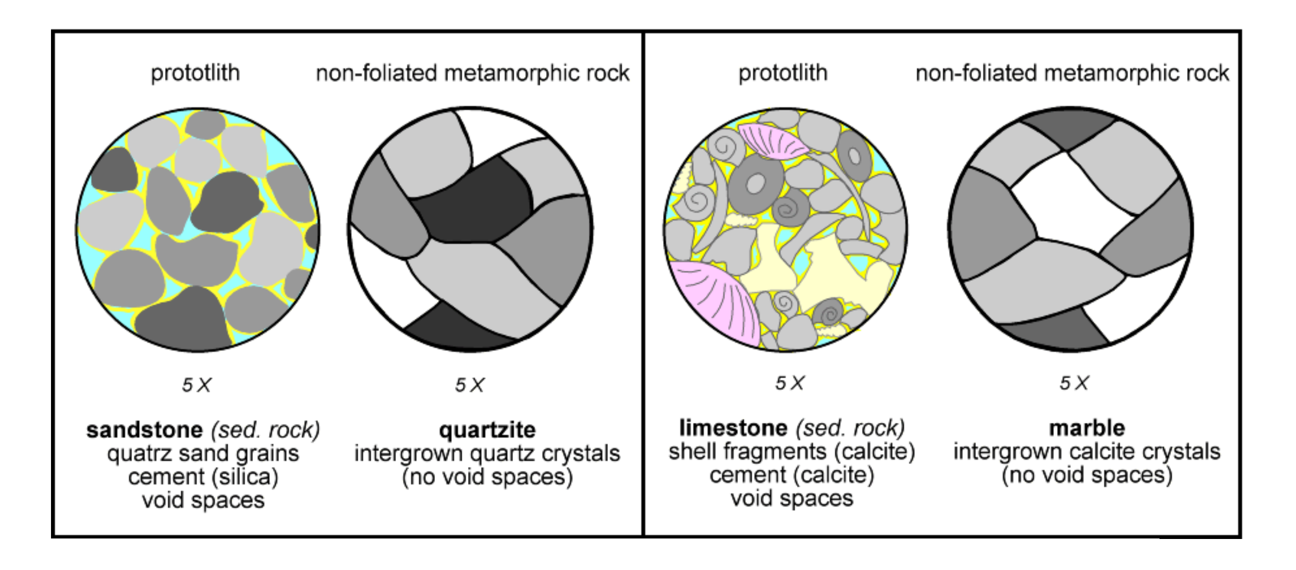
4. Gneiss :

Gneiss is a regional metamorphosed rock. The parent rocks are often sedimentary, but some gneisses have formed from granite-like igneous rocks. The main minerals include feldspars, biotite and muscovite. Gneiss is coarse-grained, with irregular banding. The colour varies from light, in gneisses derived from granite, to dark in rocks derived from sandstones. Gneiss occurs worldwide. In Europe it is common throughout the Alps, while in the USA there are good deposits in New York, New England and Georgia. It is sometimes used as a building stone. The name comes from an old German word meaning to give off sparkles. A coarse-textured banded metamorphic rock sometimes called banded granite. The bands or streaks are alternating light and dark mineral layers. The colours range from white, grey, green, red, brown to black. The bands are parallel but are not usually as wavy as those in Schist. Gneiss is formed by many different parent rocks that have been altered by regional (or Barrovian) metamorphism. It forms the extreme end of the aleration series from sedimentary rock/shale. Gneiss is metamorphosed schist. It is a highly metamorphosed that is almost a granite. It differs from schist due to the lenses of feldspar between the mica layers. The minerals in gneiss may occur either as layers (foliation) or elongated in one direction (lineation). Intensely crumpled layers are another means of identifying gneiss .





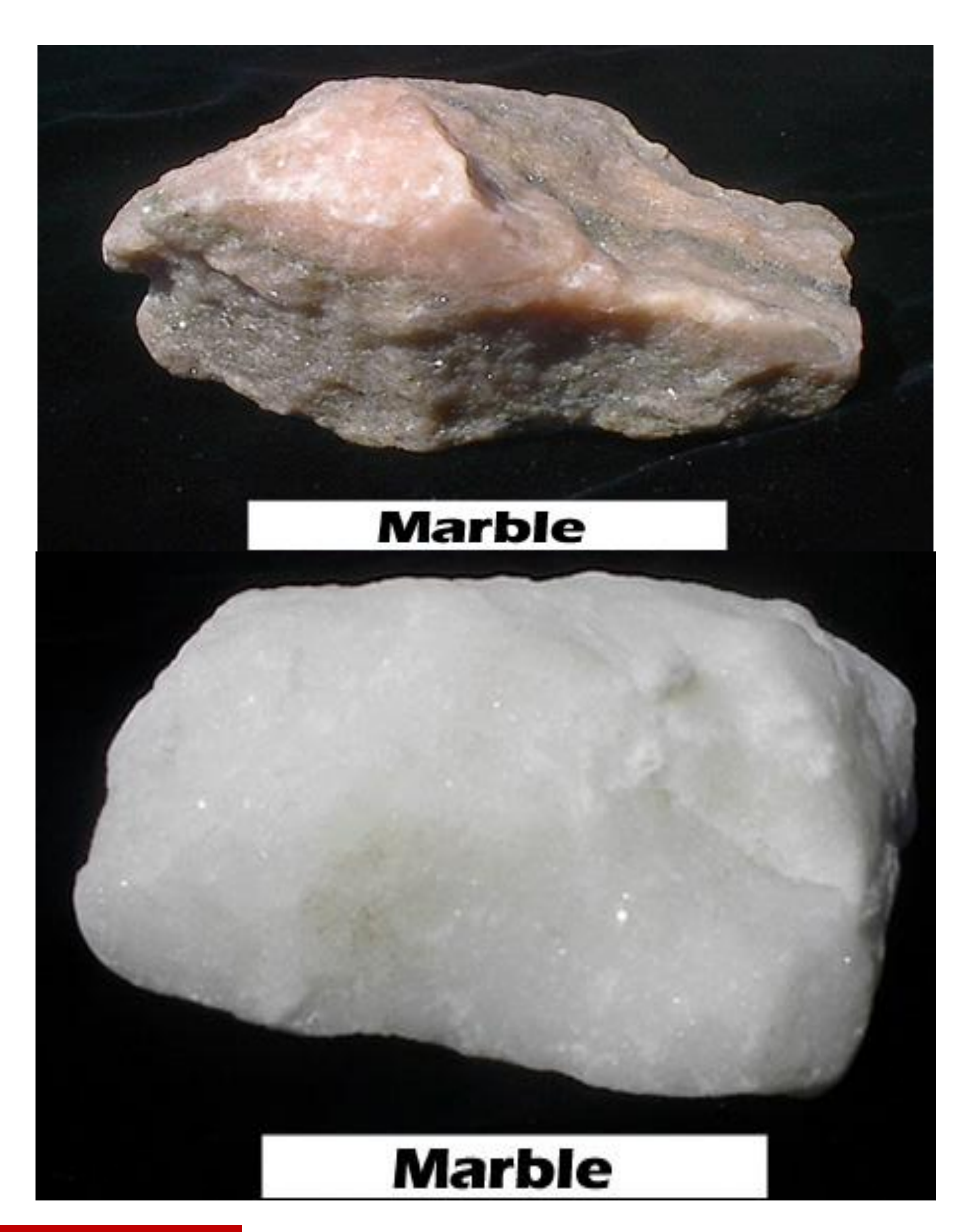
Non-foliate Metamorphic Rocks:



5. Marble:

A metamorphic rock formed mostly by contact, but occasionally regional, metamorphism of limestone or dolomite. Crystal grains and tiny pieces of Calcite are usually visible. The rock is generally whitish, but may be coloured by impurities, creating colours of pink, green, brown or black. The colour is rarely uniform because the distribution of impurities is uneven, giving some marble a highly attractive mottled appearance. For this reason, and because of its relative softness, marble has been widely used for carving statues and ornamental building stone. The fine white Carrara marble from Tuscany has been quarried since Roman times. Sometimes compact crystalline limestone can be mistaken for marble .

Marble is metamorphosed limestone. In the process of being metamorphosed, the limestone is recrystallized, creating a change in color and texture and the destruction of included fossils. There are hundreds of recognized commercial marble with a wide range of colors and patterns. However, since marble is calcite, it still bubbles vigorously when strong hydrochloric acid is applied to it. The gray streaks in typical marble are made up of graphite. Marble can range from white to pink to brown, and even black. Limestones that have broken by tectonic forces as they are being metamorphosed produce brecciated marbles. Cut and polished marble is used for statues and flooring .



6. Quartzite:

A contact or regional metamorphic rock derived from recrystallised sandstone or quartz conglomerate. It has a granular texture made of tightly packed quartz grains. It breaks across the grains and is compact and hard. It usually takes on the colour of the surrounding sandstone rocks, but can range from white, grey, yellow, pink brown and black. It often contains re-brown streaks from inclusions of iron oxide. Quartzite is metamorphosed sandstone. It is often difficult to distinguish it from a sandstone that has been cemented by quartz. The sand grains in quartzite are so tightly cemented together than when a rock of quartzite is broken in half. the break actually cuts the individual sand grains.



7. Hornfels:

Hornfels is a contact metamorphic rock, derived from clays. The main minerals include quartz, feldspars, andalusite and biotite. The colour may be pink, brown, violet or green. Hornfels contains crystals enclosing other crystals of different minerals. It occurs in Scotland, Norway, France and the Sierra Nevada, California. It has no particular use. Its name comes from a German word meaning horn rock, referring to its lustre. One of the most common metamorphic rocks. It generally forms around.

Granitic inclusions or volcanic pipes. It is usually formed by contact metamorphism of fine-grained sedimentary rocks such as shale. The rock is usually dark but can have lighter spots. Because there is no pressure associated with its formation, the rock is unfoliated. There may however be some banding, but this is the result of the layereing in the parent sedimentary rock. Can be confused with basalt. Hornfels is a non-foliated, baked rock that is formed by contact metamorphism. The color, grain size, and mineral composition shows wide variation. Colors can range from a light gray to a dark black. The darkest colored varieties of hornfels may have have originally been dark shales, siltstones, or even basalt.



8. Amphibolite:

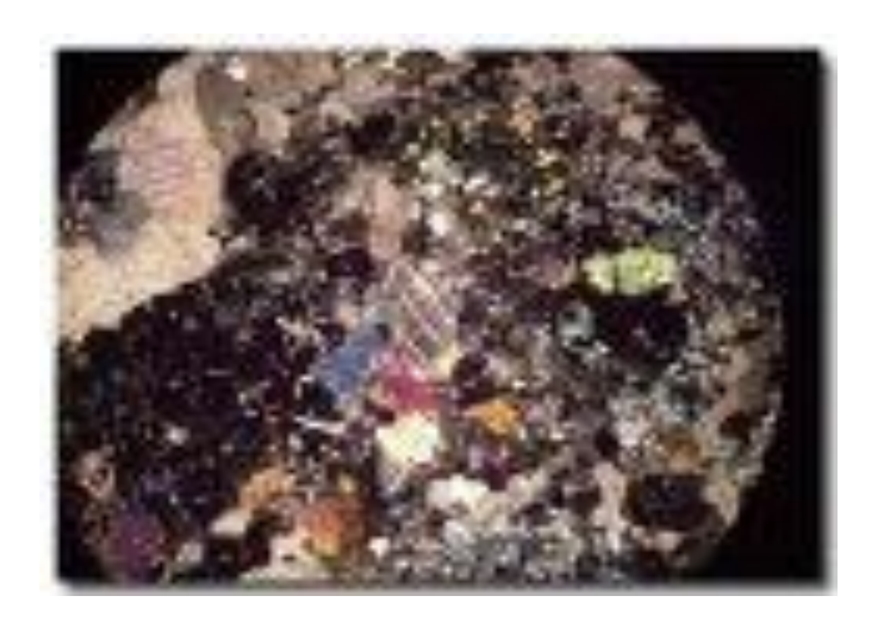
A metamorphic rock rich in amphibole minerals like horneblende. It has a schistose structure ranging from fine to coarse grained. The colour tends to be dark green to black. Plagioclase feldspars are often present. It is a toug, tenacious rock formed by the metamorphosis of Gabbro, Peridoite, Dolomite or Limestone. Usually forms by regional metamorphism of basic igneous rocks.



9. Skarn:

Skarn is formed by the metamorphism of limestones in contact with granites. Volatile fIuids containing boron, chlorine and fluorine take iron, magnesium, manganese and silicon from the granitic rock into the limestone to form new minerals. It is found in northern England, Scotland and Ireland and is common in Sweden, Japan, parts of Central and South America and the USA. Skarn is often a source rock for copper, iron, manganese and molybdenum. The name is of uncertain origin

A metasomatic metamorphic rock, meaning that it was produced by the percolation of mineral-rich liquids and gasses from an ignous intrusion through limestone or dolomite beds. The resulting rock is rich in calcium silicates and sometimes with accompanying ore deposits. Garnets and Pyroxines are often present. The rock is usually medium to coarse grained. The colour ranges from white to black depending on mineral content. It can be an attractive rock with a sparkling luster.



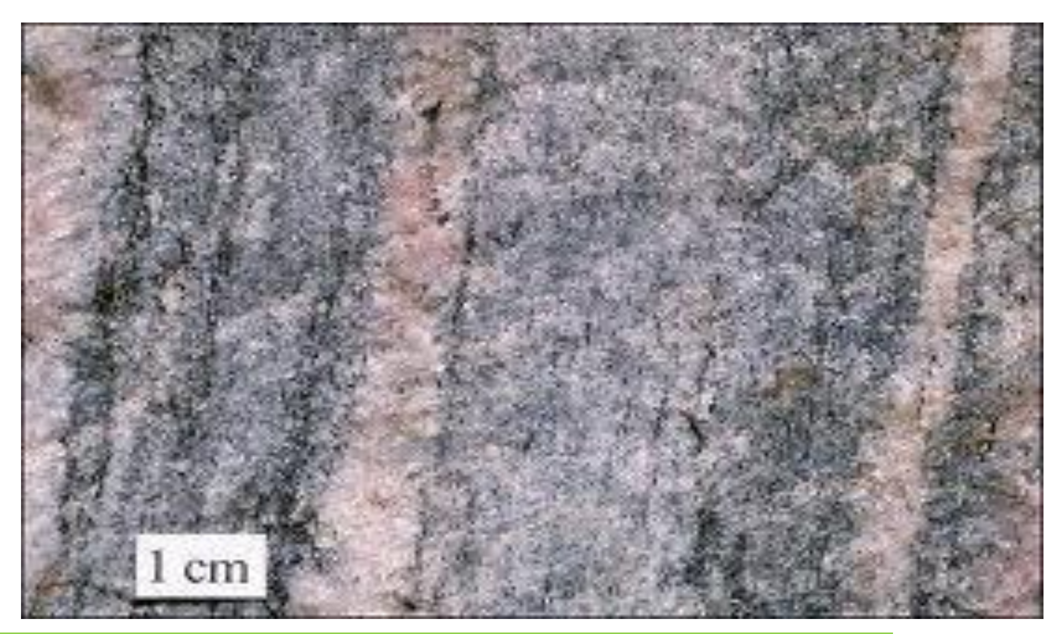
10. Serpentine:

A hydrothermal metamorphic rock that is derived from peridotite or pyroxine. Occasionally it is the end product of a metamorphic sequence starting with dolomite and then amphibolite. The rock is usually yellow-green and is often streaked or mottled with black. Has a smooth and greasy feel and often a waxy luster. The name serpentine is used for both a mineral and a metamorphic rock. It is formed by the metamorphic transformation of olivine and pyroxene to the serpentine mineral group. Serpentine varies from a light green to a dark green color with veins and fractures. It strongly resembles some varieties of jade. It is used for flooring and tabletops.



Migmatite :

Migmatite is the name given to a type of composite rock which is. a mixture of two pre-existing rocks. The country (original) rock is some kind of metamorphic rock which is remelted when it is invaded by either magma or a hydrothermal solution. The formation takes place far below the surface. Migmatites are found worldwide, in rocks more than 560 million years old. The origin of the name is uncertain. They are used as building stone.



The migmatite is may be formed by three reasons:

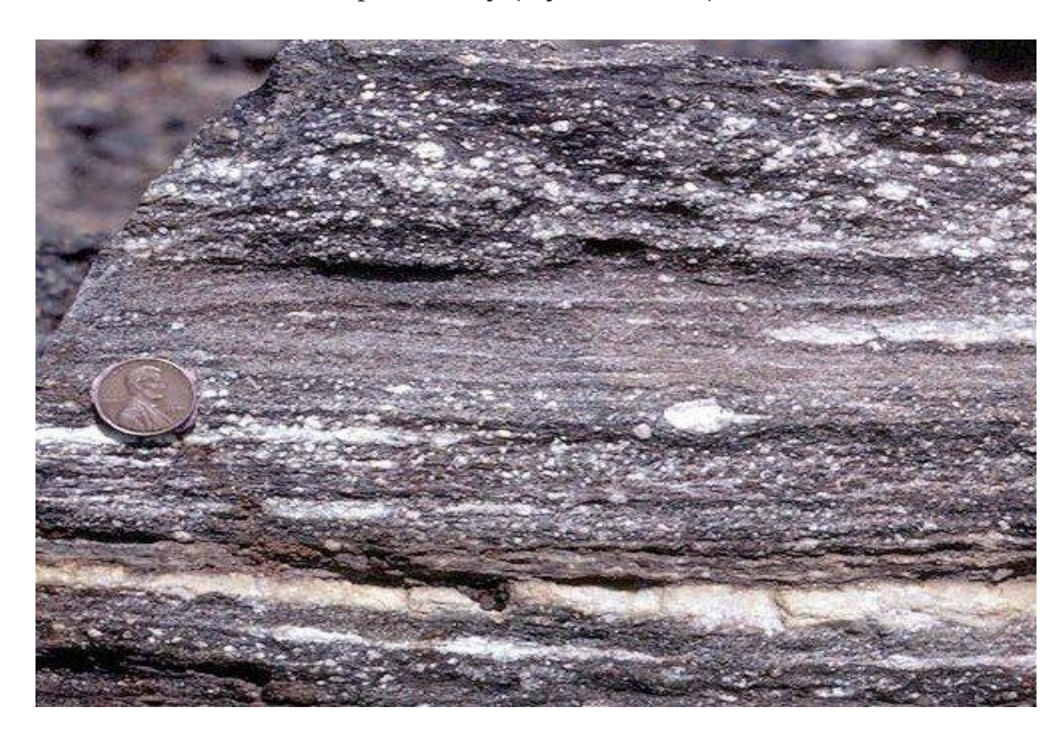
1- Lit par lit injection from the neighboring granitic magma but this is limited in the field and their layer composed of low grade melanosome or schist or phyllite alternate with granitic leucosome with the same composition of the granitic rocks in contact. The chemical composition of both leucosome and melanosome differ than the chemical composition of the muds.

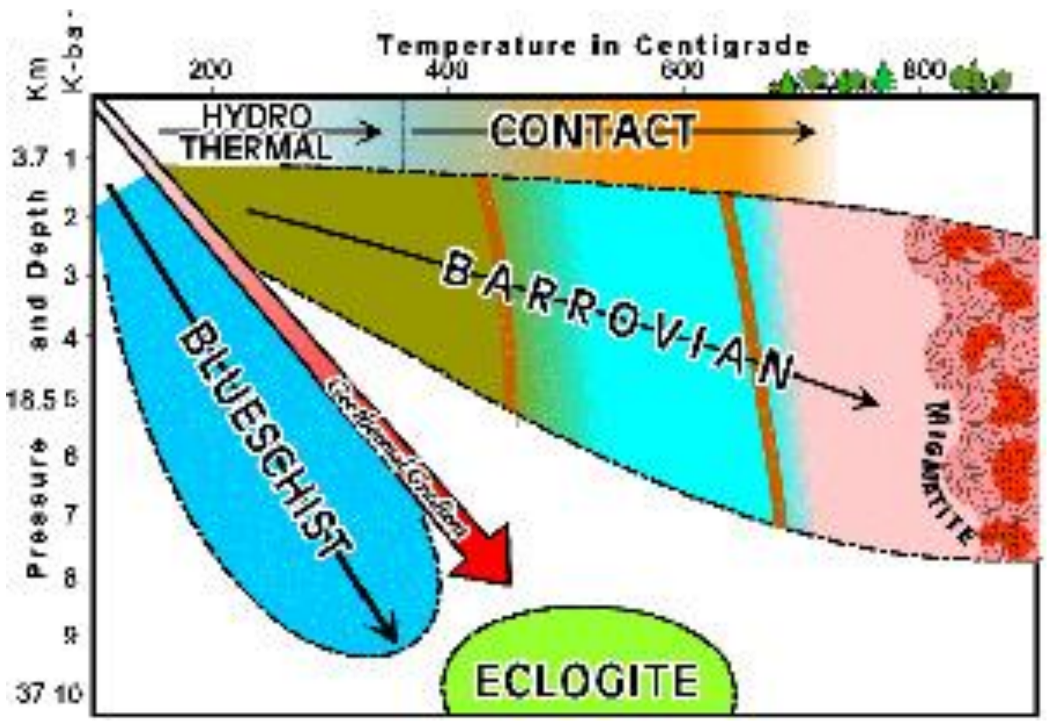
2**- Migmatite formed by partial melting of pelitic protolith** in regionally metamorphosed terrain. Here we can trace it for several kilometers in the field and chemical composition of their melanosome + leucosome is similar to its pelitic protolith.

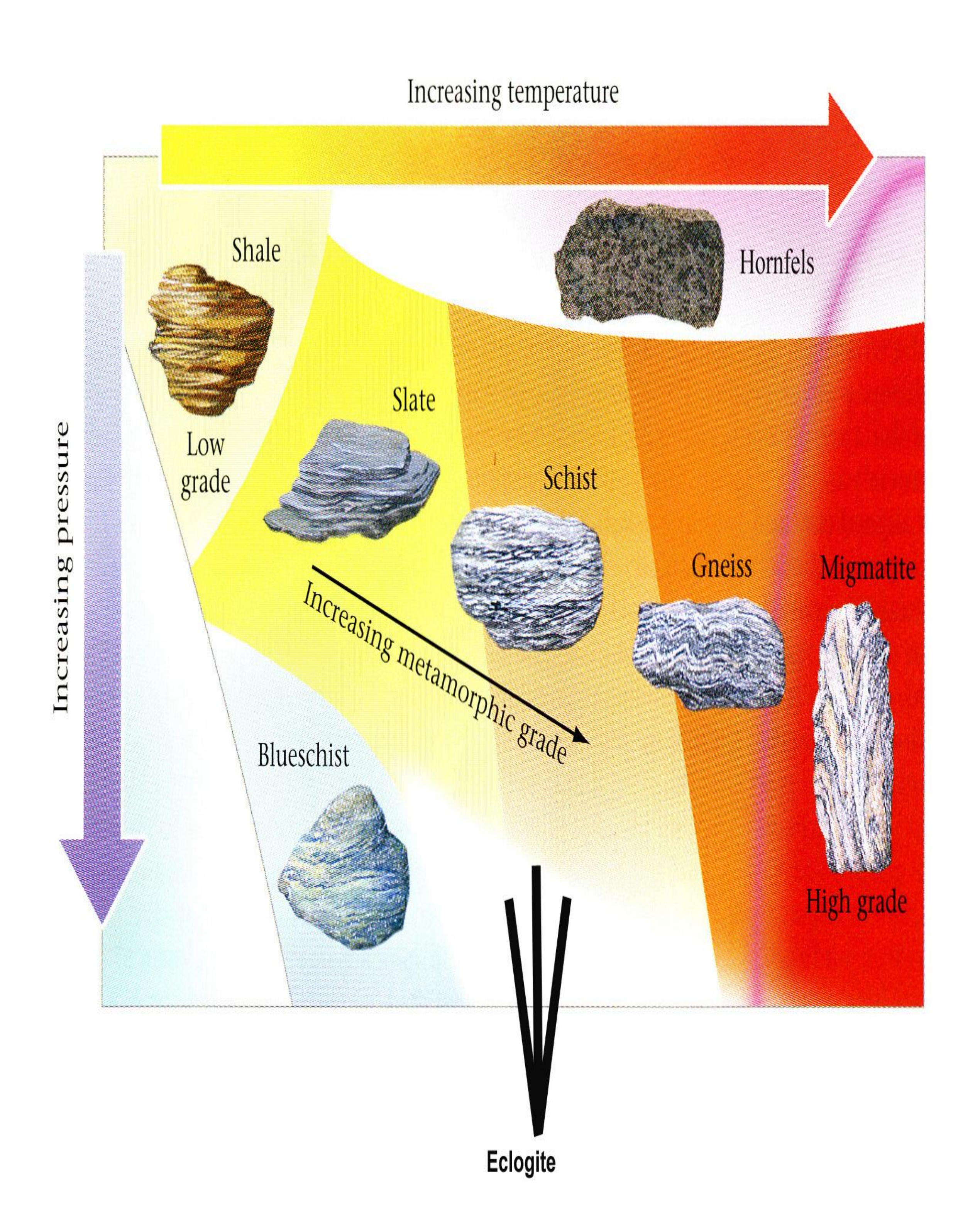
3- Migmatite formed by metasomatic addition of Na, K and silica from solution on banded sedimentary rocks give granitic layers. In this case the migmatite composition is differing than pelitic rocks

Mylonite:

Forms along fault surfaces by crushing and stretching of rocks under such heat and pressure that the deform in a plastic way (mylonitization).minerals







Increasing temperature
Shale
Hornfels
Increasing pressure
Slate
Low
grade
Schist
Gneiss
Migmatite
Increasing metamorphic grade
Blueschist
High grade
Eclogite

Common Metamorphic Rocks			
Classification	**Metamorphic Rock**	**Parent Rock**	**Common Minerals**
Foliated (Banded)	Slate	Shale, mudstone	Quartz, clay minerals (feldspars)
	Schist	Shale, slate, basalt, or granite	Mica, chlorite, talc, quartz
	Gneiss	Shale, schist, granite, sandstone, and other rock types	Quartz, feldspars
Non-Foliated (Not Banded)	Quartzite	Sandstone	Quartz
	Marble	Limestone, dolomite	Calcite
	Anthracite coal	Bituminous coal	Crystalline carbon

Rock Name		Texture		Grain Size	Comments	Parent Rock
Slate	Increasing Metamorphism	Foliated		Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite				Fine	Breaks along wavey surfaces, glossy sheen	Slate
Schist				Medium to Coarse	Micaceous minerals dominate, scaly foliation	Phyllite
Gneiss				Medium to Coarse	Compositional banding due to segregation of minerals	Schist, granite, or volcanic rocks
Migmatite				Medium to Coarse	Banded rock with zones of light-colored crystalline minerals	Gneiss
Mylonite		Weakly Foliated		Fine	When very fine-grained, resembles chert, often breaks into slabs	Any rock type
Metaconglomerate				Coarse-grained	Stretched pebbles with preferred orientation	Quartz-rich conglomerate
Marble		Nonfoliated		Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite				Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Hornfels				Fine	Usually, dark massive rock with dull luster	Any rock type
Anthracite				Fine	Shiny black rock that may exhibit conchoidal fracture	Bituminous coal
Fault breccia				Medium to very coarse	Broken fragments in a haphazard arrangement	Any rock type

وصف بعض الصخورا لمتحولة

أولاً :الصخور الصفائحية(المتورقة) : Foliated Rocks



1) الأردواز Slate:

الأصل:

صخرة متحولة ناتجة من تحول الصخور الروسوبية الفتاتية ذات الحبيبات الناعمة جداً مثل الطين(Clay) أو الطفل(Shale).

التحول:

تحول إقليمي ذو مرتبة واطئة تحت ظروف من الضغط المرتفع والحرارة المنخفضة .

التكوين المعدني:

تتكون من الميكا البيضاء(السريسيت Sericite), الكلوريت(Chlorite) والكوارتز(Quartz) بالاضافة إلي التورمالين(Tourmaline), الابيدوت(Epidote) وخامات الحديد(ore Iron).

البنيات والأنسجة :

صخرة متحولة ذات حبيبات ناعمة جداً ومتجانسة, وتتميز بالتشقق الكامل المعروف بالانفصام الأردوازي(Slate cleavage) حيث تتشقق إلي صفائح رقيقة بسبب النمو المتوازي لمعادن الميكا والكلوريت.

* يأخذ الأردواز ألوان تتراوح من الرمادي, الأسود إلي الأخضر.

2) الفليت Phyllite :



الأصل:

صخرة متحولة ناتجة من تحول الصخور الروسوبية الفتاتية ذات الحبيبات الناعمة جداً مثل الطين(clay) أو الطفل(shale).

التحول:

تحول إقليمي ذو مرتبة واطئة(أكثر تقدماً من تحول الأردواز) تحت ظروف من الضغط المرتفع والحرارة المنخفضة .

التكوين المعدني:

تتكون من الميكا البيضاء(السريسيت), الكلوريت(chlorite) والكوارتز(quartz) بالاضافة إلي التورمالين(tourmaline, الابيدوت(epidote) وخامات الحديد(iron ore) ألا أن حبيبات الفليت أكبرحجماً من مثيلاتها في الأردواز وتزيد نسبة الميكا البيضاء(السريسيت) علي الكلوريت.

البنيات والأنسجة:

صخرة متحولة ذات حبيبات ناعمة ومتجانسة ألا أن حبيبات الفليت أكبرحجما(أكثر خشونةُ) من مثيلاتها في الأردواز, وتتميز بالتشقق الكامل حيث تتشقق إلي صفائح رقيقة بسبب النمو المتوازي لمعادن الميكا والكلوريت علي شكل رقائق مستطيلة. قد يتواجد البنية الشستوزية في الفليت.

* يأخذ الفليت ألوان تتراوح من الرمادي إلي الأسود ويتميز ببريقه الامع.



3) الشست Schist:

الأصل:

صخرة متحولة ناتجة من تحول صخور مختلفة(الروسوبية الفتاتية, الطين(Clay), الطفل(Shale) أو النارية القاعدية).

التحول:

تحول إقليمي ذو مرتبة واطئة أو متوسطة تحت ظروف من الضغط المرتفع والحرارة المتوسطة(أكثر تقدماً من تحول الفليت).

التكوين المعدني:

تتميز صخورالشست بالتنوع الكبير في مكوناتها المعدنية تبعاً لتنوع التركيب المعدني للصخور الأصلية. أهم المعادن فيها هي الميكا mica))، الكلوريت(Chlorite), الأكتينوليت(Actinolite), الألبايت(Albite), الكوارتز(Quartz), التلك(Talc) والهورنبلند(Hornblende) بالاضافة إلي الجرافيت(graphite), ألابيدوت(Epidote) وخامات الحديد(Iron ore).

البنيات والأنسجة:

صخرة متحولة ذات حبيبات ناعمة أو متوسطة, وهي من أكثرالصخور التي تحتوي علي البنية الشستوزية والتي تتكون من رقائق بلورية من المعادن الميكا mica)) والكلوريت(Chlorite وبعض المعادن المنشورية مثل الهورنبلند(Hornblende) حيث تترتب في صفوف رقيقة متوازية تكسب الصخر شكلا صفائحيا.



4) النايس Gneiss:

الأصل:

صخرة متحولة ناتجة من تحول صخور مختلفة, فيمكن أن تنتج من الصخور الروسوبية (gneiss Para) أوالنارية Ortho gneiss).

التحول:

تحول إقليمي(ضغطي- حراري) ذو مرتبة عالية ((Regional high-grade تحت ظروف من الضغط المرتفع والحرارة المرتفة.

التكوين المعدني:

تتميز صخورالنايس بالتنوع الكبير في مكوناتها المعدنية تبعاً لتنوع التركيب المعدني للصخور الأصلية. النايس ذات الأصل الناري تتكون من طبقات من االفلسبار(feldspar) والكوارتز(Quartz) متبادلة مع اخري من البيوتايت(biotite) والهورنبلند(Hornblende), وتلك التي تأتي من أصل رسوبي تتكون من أشرطة من المعادن االفلسبار(feldspar) والكوارتز(Quartz) تتبادل مع معادن صفائحية مثل الميكا (mica, الكلوريت(Chlorite) والجرافيت(graphite).

البنيات والأنسجة:

صخرة متحولة ذات حبيبات خشنة, وهي من أكثرالصخور التي تحتوي علي البنية النايسوزية والتي تتكون من رقائق او أشرطة من المعادن الداكنة اللون}مثل الميكا mica)) الهورنبلند(Hornblende){ والأخري الفاتحة اللون(مثل االفلسبار والكوارتز) حيث تترتب في صفوف رقيقة متبادلة. فد يتواجد الكوارترعلي شكل عدسات.

* يميل لون النايس في كثيرمن الأحيان إلي الرمادي المبيض, وهنالك عدة أنواع من النايس منها النايس الجرانيتي (granitic gneiss) والنايس الديوريتي(dioritic gneiss).

ثانياً :الصخور غيرالصفائحية(غيرالمتورقة)Non-foliated Rocks



1) الهورنفلس Hornefles:

الأصل:

تتكون صخورالهورنفلس نتيجة تحول مختلف انواع الصخور الروسوبية بالاضافة لبعض الصخور النارية, لذا يمكن ان تكون نتاج لصخورالطينية(pelitic), الطينية-الرملية(psammetic), نارية(igneous), الجيرية(calcareous) أو القاعدية(basic).

التحول:

تتكون بفعل التحول الحراري التماسي لذا يكثر وجودها علي حدود الصخور الجوفية.

التكوين المعدني:

تختلف المعادن في الهورنفلس تبعاً لاختلاف التركيب المعدني للصخور الأصلية, اهم المعادن فيه هي الكوارتز(Quartz), الفلسبار, الميكا, الكوردريت(cordierite), ألأندالوسايت(Andalusite), السيليمانيت(Silimanite) ألديوبسايت(Diopsite) والكورندوم(corundum)

البنيات والأنسجة:

يتميز الهورنفلس بأنه صخرة متماسكة ذات حبيبات ناعمة جداً ويسود فيه البنية الحبيبية والنسيجا ال Porphyroblastic.

* يميل لون الهورنفلس في كثيرمن الأحيان إلي الرمادي



2)الكوارتزيت Quartzite:

الأصل:

تتكون صخورالكوارتزيت نتيجة تحول الحجر الرملي(Sandstones)

التحول:

تتكون بفعل التحول الحراري التماسي أو الاقليمي.

التكوين المعدني:

يتكون أساساً من بلورات معدن الكوارتز بالاضافة إلي نسبة قليلة من الفلسبار, وقد يتواجد الميكا.

البنيات والأنسجة:

يتميز الكوارتزيت بأنه صخرة متماسكة تتكون من بلورات متوسطة أو ناعمةً ويسود فيه البنية الحبيبية والنسيج الموزيكي (Mosaic).

* يتميز الكوارتزيت بلونه الأبيض وقد يكتسب اللون الأحمر, الوردي, الرمادي أو البنفسجي إذا احتوي علي شوائب



3)الرخام (المرمر) Marble:

الأصل:

تتكون صخورالرخام نتيجة تحول الصخور الكلسية(الحجر الجيري والدولومايت).

التحول:

تتكون بفعل التحول الحراري التماسي أو الاقليمي.

التكوين المعدني:

يتكون أساساً من بلورات معدن الكالسايت بالاضافة إلي نسبة قليلة من الكوارتز,إذا كانت الصخور الأصلية تحتوي علي كربونات الماغنيسيوم(الدولومايت) فقد يساعد علي تكوين معادن الديوبسايت(diopsite),التريمولايت(terimolite), الجارنت(garnet) والسربنتين(serpentine).

البنيات والأنسجة:

يتميز الرخام بأنه صخرة متماسكة تتكون حبيبات متوسطة إلي خشنة متساوية الأبعاد تقريباً ومتراصة بشكل منتظم مما يكسب الصخر البنية الحبيبية والنسيج الموزيكي (Mosaic).

* الرخام النقي أبيض اللون وقد يميل لونه إلي الأحمر, الوردي, الرمادي, الأصفر, الأخضر أو الأسود علي حسب الشوائب الموجودة فيه. يتميز الرخام بلمعانه السكري المميز(luster Sugary).

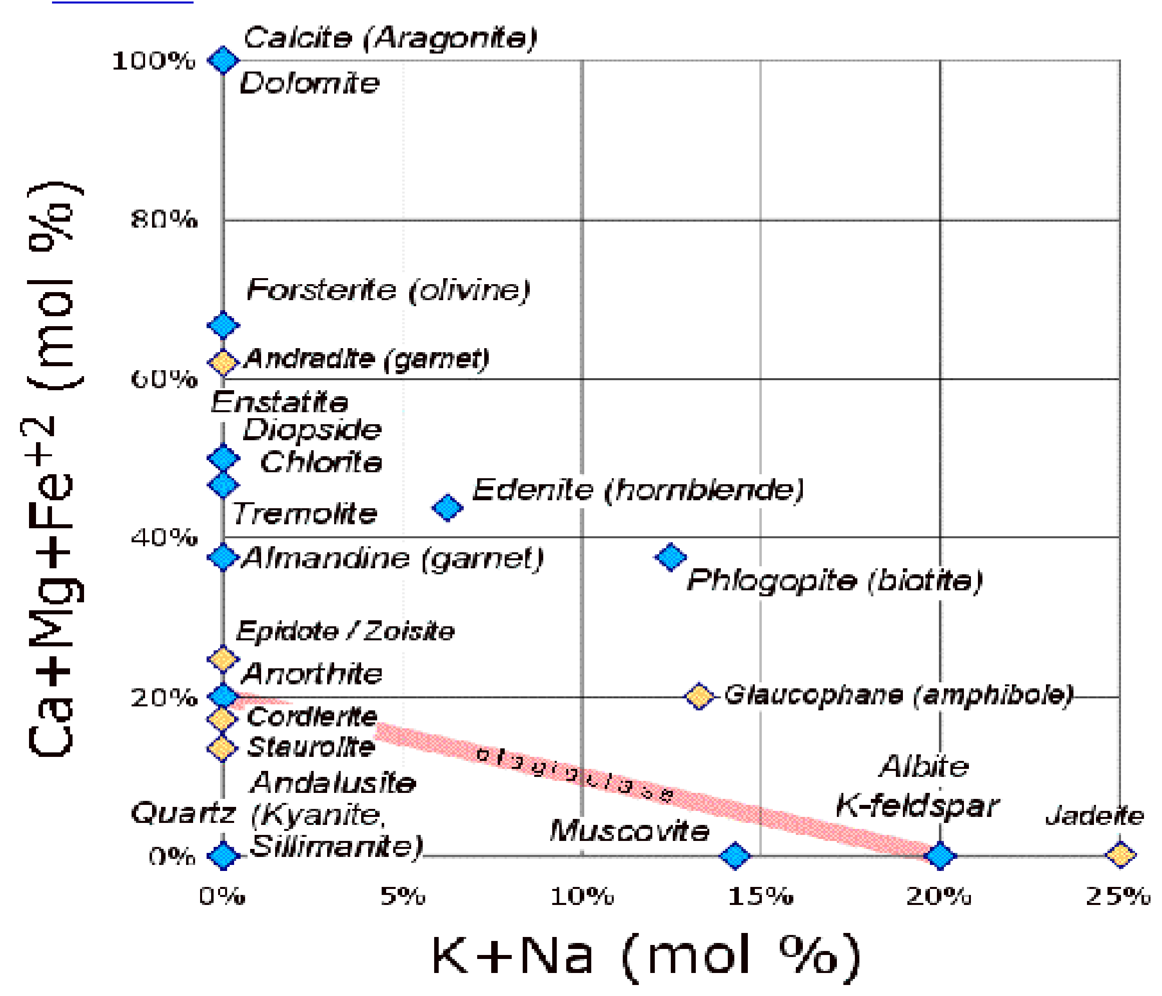
CHAPTER 8

Minerals in metamorphic rocks

Metamorphic rocks contain minerals from each of the major silicate rock-forming groups (framework, sheet, chain, and ortho slicates). The proportion and identity of those minerals depends on the rock type (conversely, they can be used to define the rock type).

In what metamorphic setting would you expect to find amorphous or poorly crystalline materials? How might you recognize them in thin section?

This figure shows the principal metamorphic minerals that we consider in this class:



1. Minerals in metamorphic rocks :

a) metamorphism vs. metasomatism.
b) reminder of metamorphic facies concept & terms.
c) facies defined by mineral assemblages in mafic rocks.
d) characteristic progression in other rock types (pelites).

Minerals:

Kyanite Al_2SiO_5 suggest high pressure in pelitic schist.

Sillimanite Al_2SiO_5 suggest high temperature in pelitic schist.

Andalusite Al_2SiO_5 suggests lower T & P in pelitic schist.

Chlorite (Mg,Fe).SiAl(OH) in green schist facies of basic rocks.

Chloritiod (ottrelite) (Fe,Mg),AlO found in Mg-rich politic rocks at high temperature and low pressure.

Zoisite CaAlSiO(OH) low T & P.

Lawsonite CaALSiO(OH).H_2O low T & P.

Epidote CaFeAlSiO2(OH) at low and medium grade basic rocks.

Almandine garnet FeAlSiO.

Pyrope (Mg-garnet) MgAlSiO.

Grossular (Ca-garnet) CaAlSiO.

Biotite KMgFAlSiAlO(OH) at most metamorphic politic rocks.

Diopside CaMgSiO in metamorphosed calcareous and basic igneous rocks.

Jadeite NaFeSiO at high pressure metamorphic rocks.

Omphacite NaFeSiO (high pressure).

Wollastonite CaSiO high temperature of calcareous rocks.

Staurolite (Fe)AlSiO(OH) formed from Fe-rich politic rocks.

Tourmaline it is pneumatolitic mineral formed by the action of boron on pelitic and amphibolitic rocks by the solution from granitic magma. It is found through pneumatolitic granite (Na, Mg, Fe, Mn, Li, AlSiOBoO,OH.

2. Distinctively metamorphic minerals:

a) garnets (many types).
b) aluminum silicates and other Al-rich minerals (staurolite, cordierite, epidote group).
c) high-pressure minerals (jadeite, glaucophane, aragonite, pyrope, spinel).

3. Textural features of metamorphic minerals and rocks:

a) inclusions.
b) foliations, lineations.
c) mineral deformation.

4. Mineral stability in metamorphic rocks (Wednesday):

a) reaction principles.
b) barrovian sequence in pelitic rocks.
c) progression in mafic (and calcic) rocks.
d) high-pressure.

5. Deformation mechanisms in metamorphic and cataclastic rocks:

a) principles.
b) crystallographic basis for deformation.
c) applications to different settings.

6. Metasomatism - changes in bulk composition.

Facies series":

Although the "Barrovian" squence described above can be thought of as the characteristic sequence of metamorphism, there are clearly other trends represented relatively hot (arcs) or relatively cold (subduction zones) geothermal gradients. These are commonly referred to as:

1. *Low-pressure facies series* (andalusite and cordierite are characteristic in pelites)

2. *High-pressure facies series* (jadeite and kyanite are characteristic in pelites)

Note that the "Buchan Zones" in the map above correspond to high-T near contemporaneous granites. These belong to the low-pressure facies series.

Distinctively metamorphic minerals:

Key metamorphic minerals - mostly with octahedral Al

In addition to minerals that we have already covered, a number of others are characteristic of metamorphic rocks. These include, the garnet group, the Al_2SiO_5 group, staurolite, the epidote group, the $Na^{viii}Al^{vi}$ chain silicates (jadeite and glaucophane), spinel, and aragonite (where it is stable.

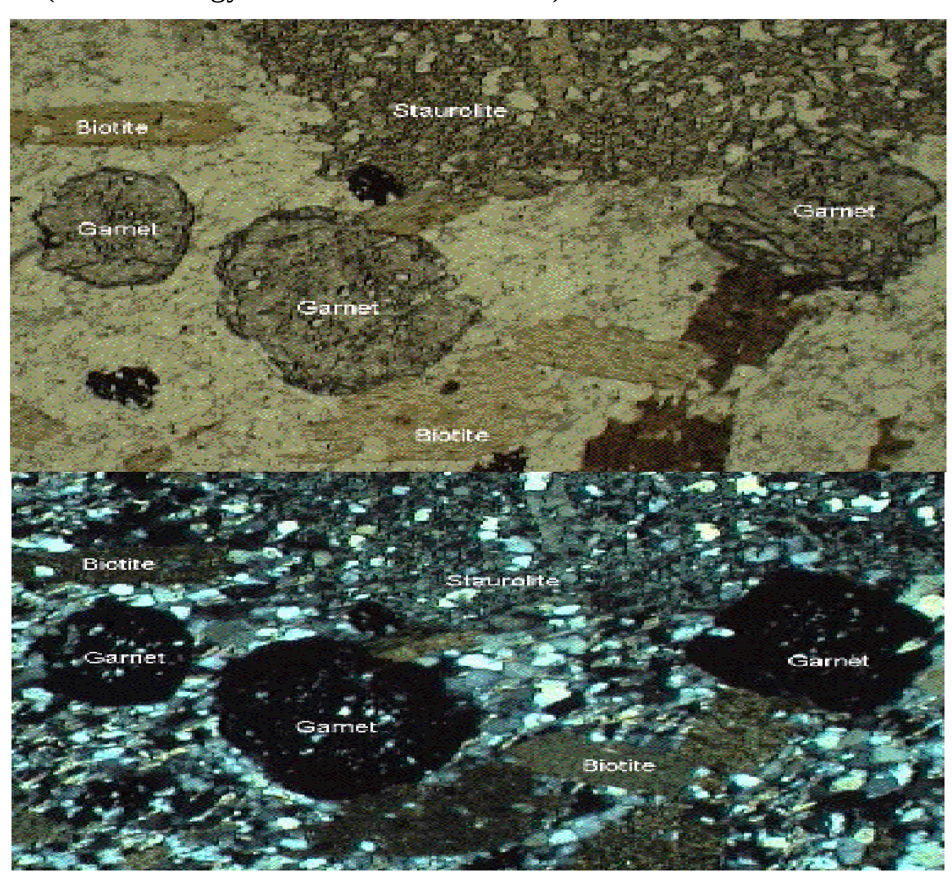
Why is octahedral Al important?

Garnet group (many types):

Garnet group minerals have the general formula $X^{viii}{}_3Y^{vi}{}_2Si_3O_{12}$ with X = Ca, Fe^{+2}, Mg, (Mn^{+2}) and Y = Al, Fe^{+3}, (Cr). Calcic garnets (grossular, andradite) are most common in calcareous or mafic bulk compositions, whereas the subcalcic garnets (almandine, pyrope, spessartine) are most common in pelitic or felsic rocks.

The garnet structure looks complex but contains only a three crystallographic sites and one type of oxygen position. In thin section garnet is almost always isotropic, but as its composition and density (high) would suggest, it has high relief.

Below: A porphyryblastic staurolite-garnet-biotite schist. Note the extreme abundance of inclusions in the staurolite, the moderate number in the garnet, and the relative scarcity in the biotite. This features are characteristic of each of these minerals and reflect the tendency of their respective crystal structures to exclude other minerals (surface energy and directional controls).

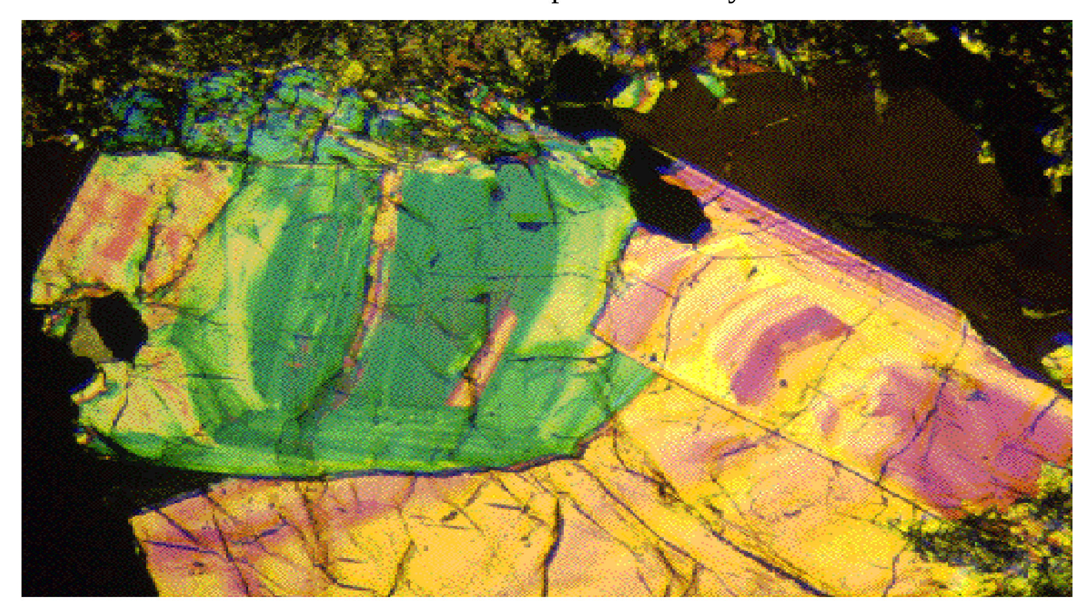


Epidote group minerals include the clinozoisite-epidote solid solution (monoclinic, $Ca_2Al_2(Al,Fe^{+3})Si_3O_{12}(OH)$) and the low-Fe orthorhombic mineral zoisite. They are broadly similar in composition to calcic garnets + water, but with slightly more Al and

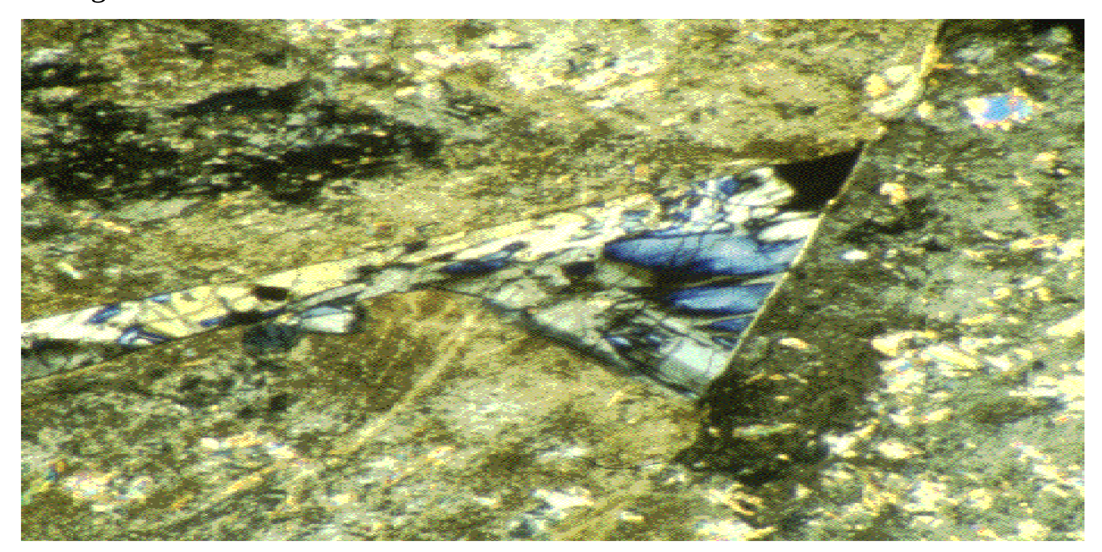
less Ca. Their structure is a bit unusual in that it is one of the rare examples of minerals that have pairs corner-sharing of SiO_4 tetrahedra, not infinite chains, sheets, rings, or frameworks .

In thin section, epidote-group minerals have moderate birefringence. They can superficially resemble pyroxenes, but differ in the lack of cleavage and their optical properties.

Below: Epidote in thin section showing zoning in birefringence related to differences in Fe/Al. This is distinctive of epidote in many rocks.



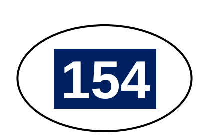
Below: Low Fe clinozoisite also has distinctive colors, in that case, "Berlin-blue" anomalous colors due to the Fe^{+3} substitution. The latter is shown in the second image where clinozoiste and mine grained muscovite (sericite) replace an igneous plagioclase grain. *Below right:* Tanzanite is a V^{+3} rich zoisite known from high-grade, high-pressure metamorphic rocks in Tanzania. It is rare because finding a protolith with high V^{+3} and low Fe^{+3} is unusual.



Aluminum silicates and other Al-rich minerals (staurolite, cordierite):

The highly aluminum-rich minerals are found in rocks with an original mud (clay) component known in metamorphic terms as pelitic or semi-pelitic (cf. composition figures above).

The aluminum silicate group (Al_2SiO_5) consists of andalusite, sillimanite, and kyanite. The structures all share chains of Si-Al and are connected by Al polyhedra

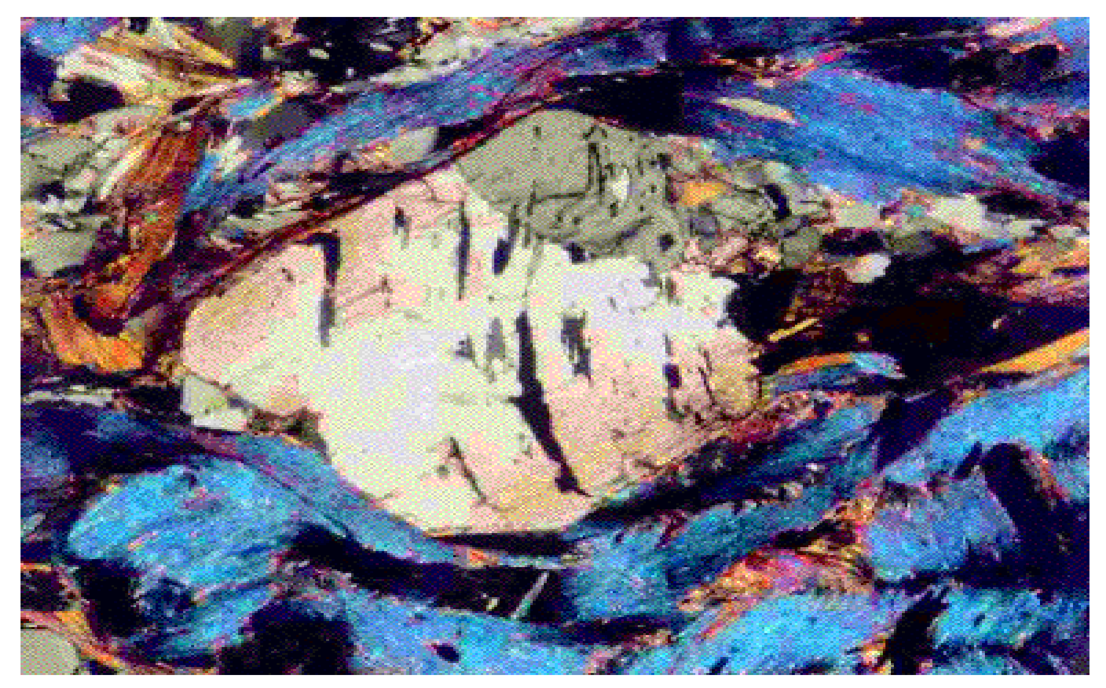


with CN of 4, 5, and 6. Interestingly, the highest molar volume belongs to andalusite which has the irregular 5 coordinated polyhedron. (movies of andalusite, sillimanite).

Belowt: The characteristic blue color of kyanite comes from Fe^{+3} substituting for Al.



Below: kyanite in thin section from a muscovite schist. Why wouldn't you expect to find K-feldspar in kyanite-bearing rocks (what would kyanite + microcline + water equal?)?



Other Al-rich minerals that are common include staurolite and cordierite. The structure of cordierite is interesting in that it is ring-based framework structure with Si-Al rings

and connecting Al tetrahedra. (It is very similar to beryl [e.g., emerald].)

Staurolite (illustrated above with garnet) is easy to recognize in thin section due to its distinctive yellowish color and exceptionally abundant inclusions.

Below: Thin section of a cordierite-andalusite hornfels showing the inclusion-rich nature of these minerals. Cordierite is almost always altered to chlorite and other minerals. It has low birefringence and relief (why would you expect this?). A later photo shows a hand specimen of andalusite with the same cross pattern.



***Below**:* Emerald in mica schist from Habachtal, Austria. This localtion was the source of many of the emeralds of antiquity. Beryl is a pelitic mineral, analogous to cordierite, but much rarer given the scarcity of the element beryllium.

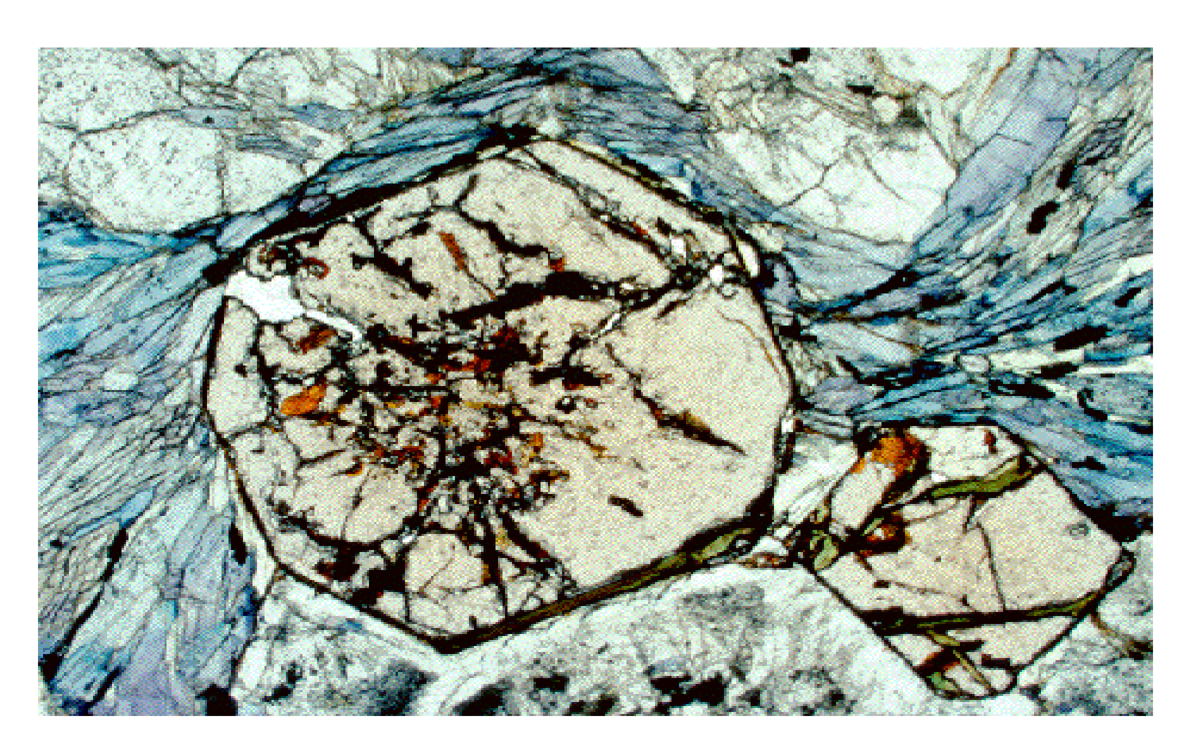


High-pressure minerals (jadeite, glaucophane, aragonite, pyrope, spinel):

These minerals are all characterized by higher coordination numbers of Al or Ca than are present in their lower pressure Na or Ca bearing equivalents, such as albite, edenite, calcite, chlorite, or cordierite. This can be seen by comparing, for example, edenite to glaucophane .

In thin section, these minerals have properties that resemble the other members of their groups. Among the most distinctive are the blue amphiboles (glaucophane and relatives) which given their names to "blueschists" and the blueschist facies. The blue color comes from rapid electron transfer between ferric and ferrous iron in the structures.

Below: Plane polarized view of an Mg-Fe garnet + foliated blue amphibole (glaucophane-rich; note zoning) + jadeitic clinopyroxene (?) from a high-pressure blueschist.



Textural features of metamorphic minerals:

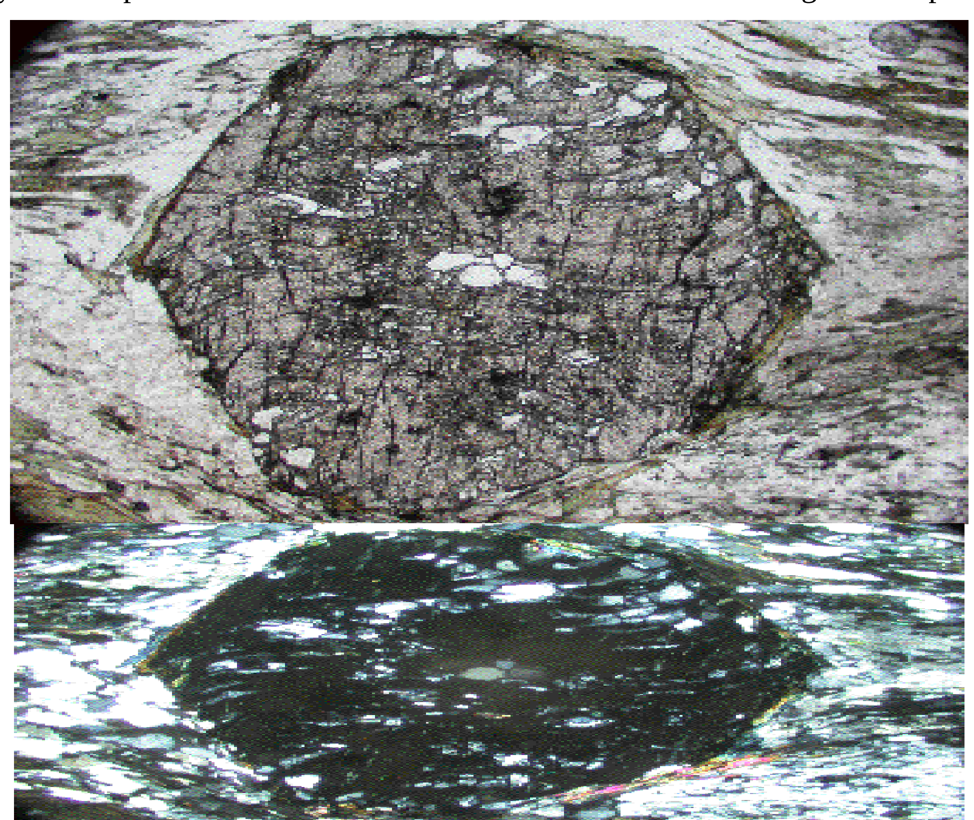
Inclusions:

Inclusions are common in minerals in many settings but are particularly common in metamorphic rocks, especially in minerals that grow large and overgrow their matrix. Many metamorphic minerals have abundant inclusions garnet group, cordierite, staurolite, and andalusite (all illustrated above) are noted for their abundant inclusions.

Below: A hand specimen of an phyllite with porphyroblasts of andalusite showing a very characteristic cross pattern of inclusions. For reference only, this variety is known as "chiastolite" and is shown in thin section above.

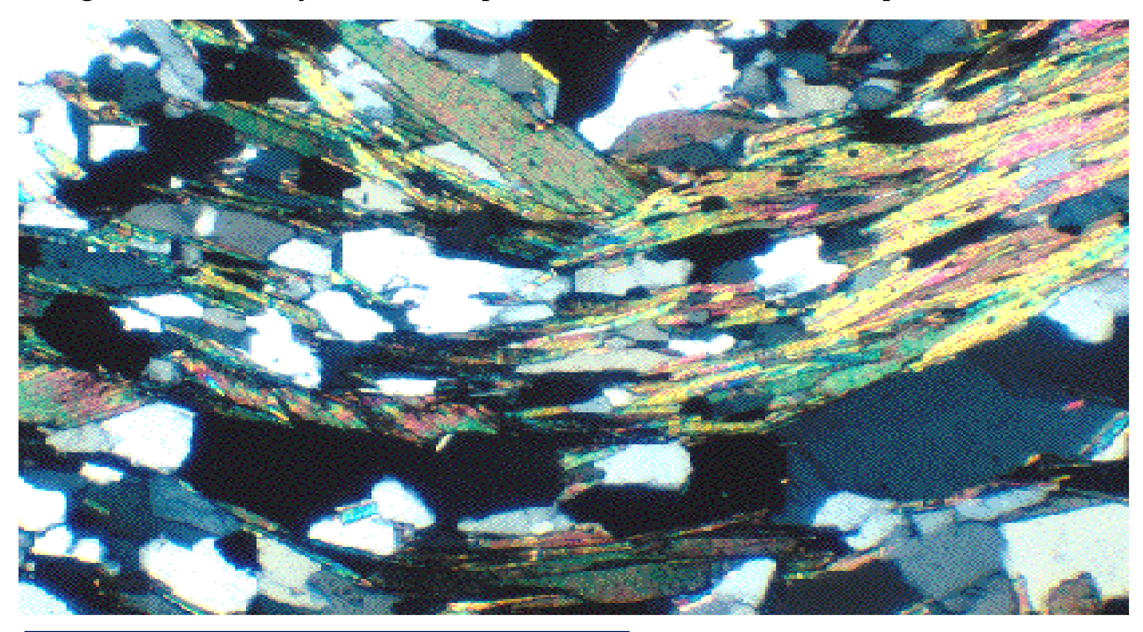


***Below**:* Garnet porphyroblast in a garnet-muscovite schist showing inclusion trails. Can you see a pattern in the inclusion "trails" in this rock? What might this represent?



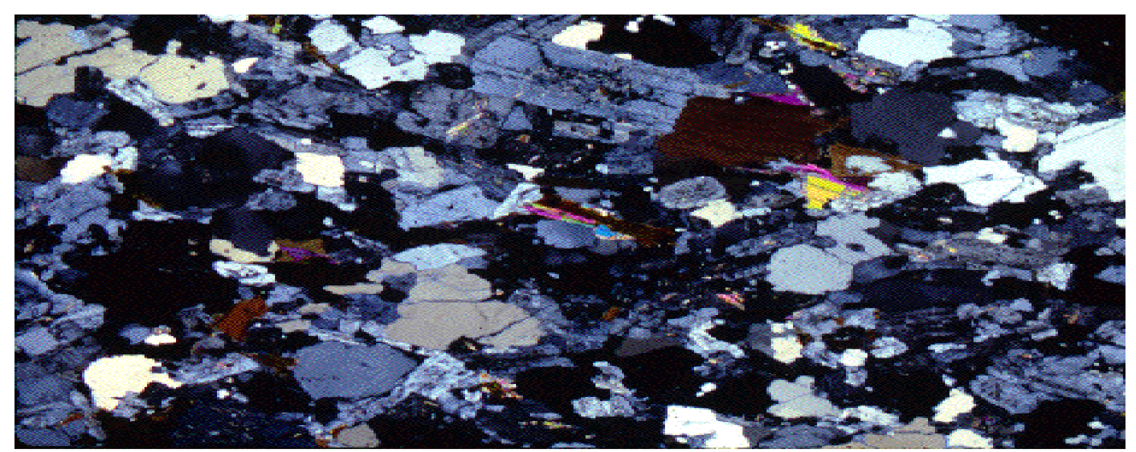
Mineral alignment in metamorphic rocks: foliations and lineations:

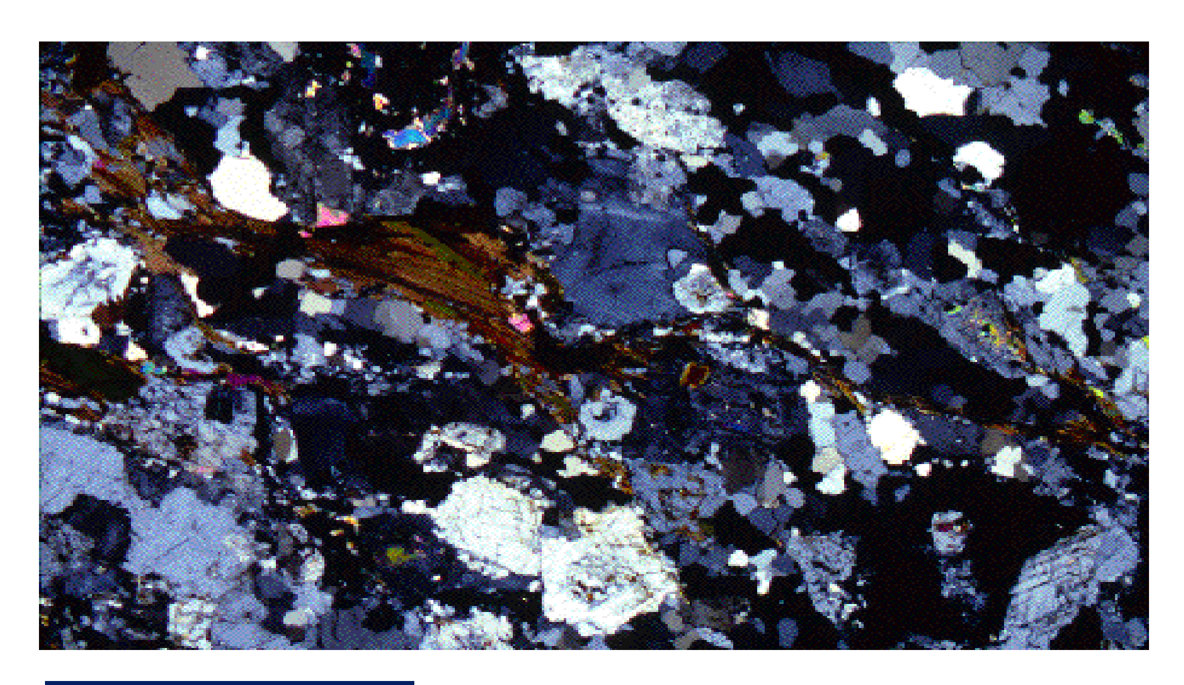
Mineral alignments -- foliations and lineations are among the most distinctive features of metamorphic rocks. Foliations are generally defined by platy minerals such as micas, whereas lineations are more often defined by elongate minerals such as amphiboles or pyroxenes. This need not be the case though! Peridotite (olivine dominated), amphibolites (amphibole dominated), and marbles (carbonate-rich) can all show excellent foliations and mineral alignments (lineation or foliation) are recognized in virtually all rock compositions in deformed metamorphic terrains.



Contrasting origins of alignments: Mineral alignment can be caused by primary processes or by metamorphism. Commonly these are superimposed. For example, sedimentation / compaction aligns sheet silicates and melt movement can align feldspars. Subsequent solid-state (metamorphic) deformation can modify (enhance or destroy) these alignments.

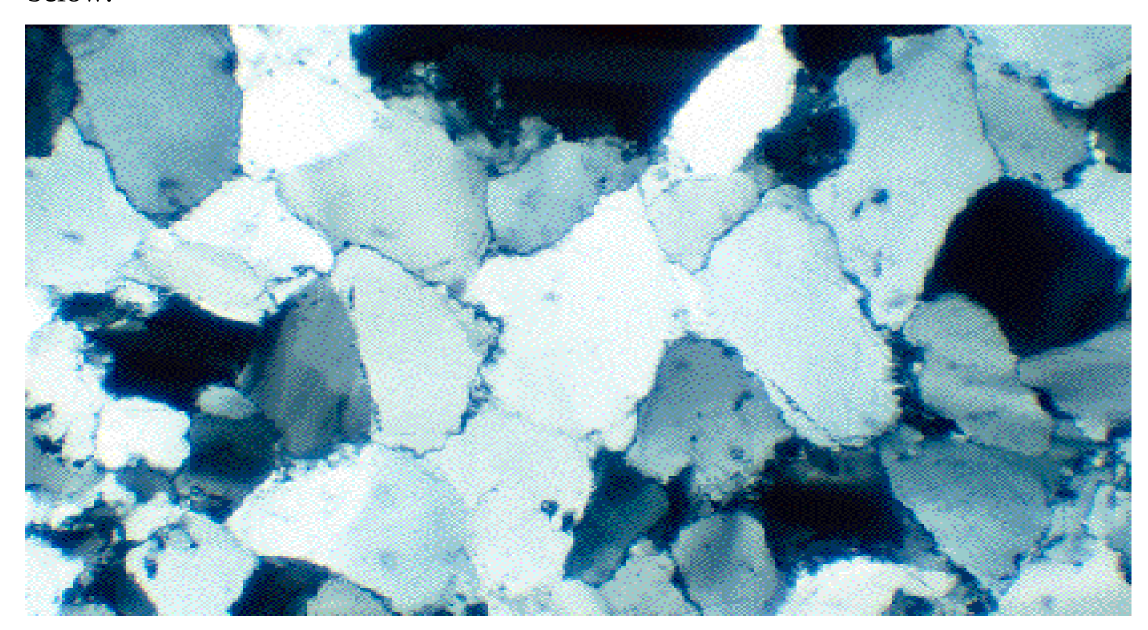
Below: The two following thin sections show primary magmatic foliation and a superimposed tectonic foliation. The latter was caused, in this case, by continued emplacement of magma after the illustrated rock had fully crystallized and was continually deformed. Note the formation of new crystals, new grains and smaller grains, and deformed aggregates.





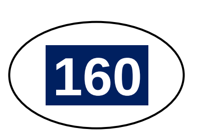
Mineral deformation:

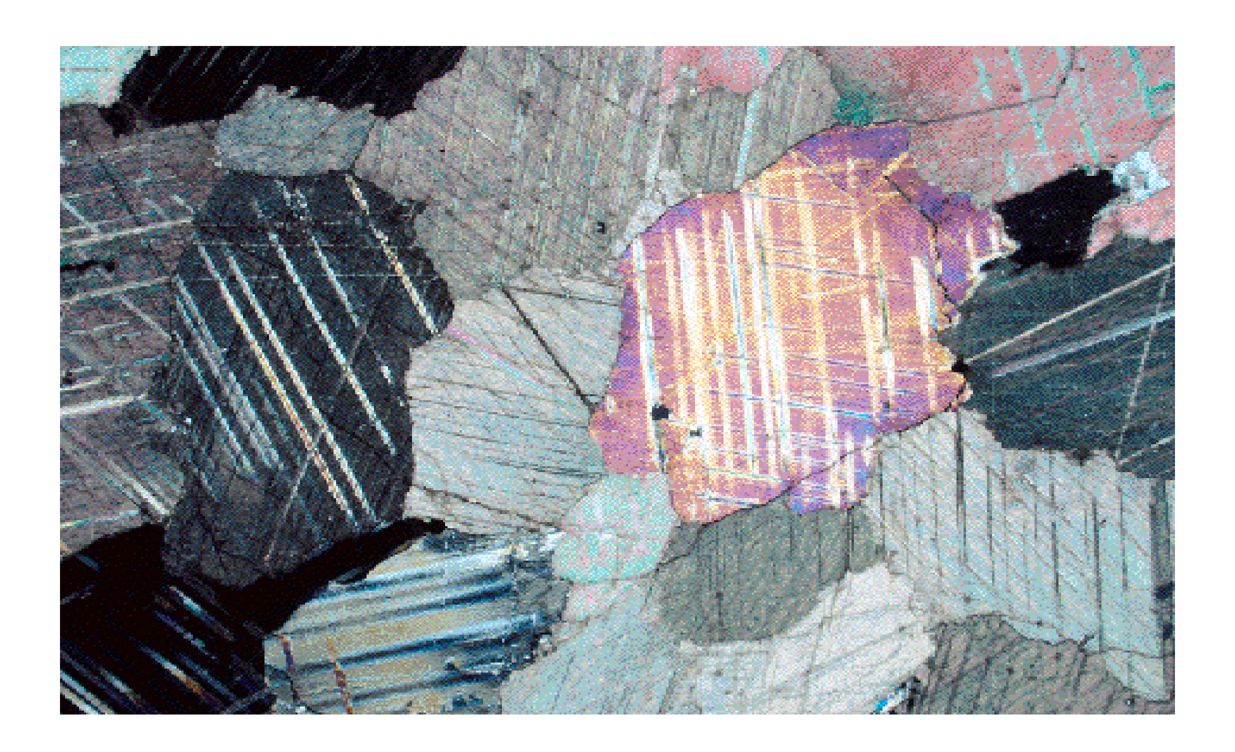
Mineral deformation takes place by a variety of mechanism that will be considered below.



Deformed quartz in thin section can be recognized by the development of subgrains, wavy extinction, sutured boundaries, and preferred orientation. Preferred orientation becomes particularly obvious with the gypsum plate which highlights the elongation of the C-axis Analogous features in other minerals have a crystallographic origin. For example, in calcite similar ragged boundaries, new grains, and internal deformation (to the grains) can be seen as illustrated below.

Below: Thin section of a calcite marble showing abundant twin bands caused by deformation and accumulation of strain.





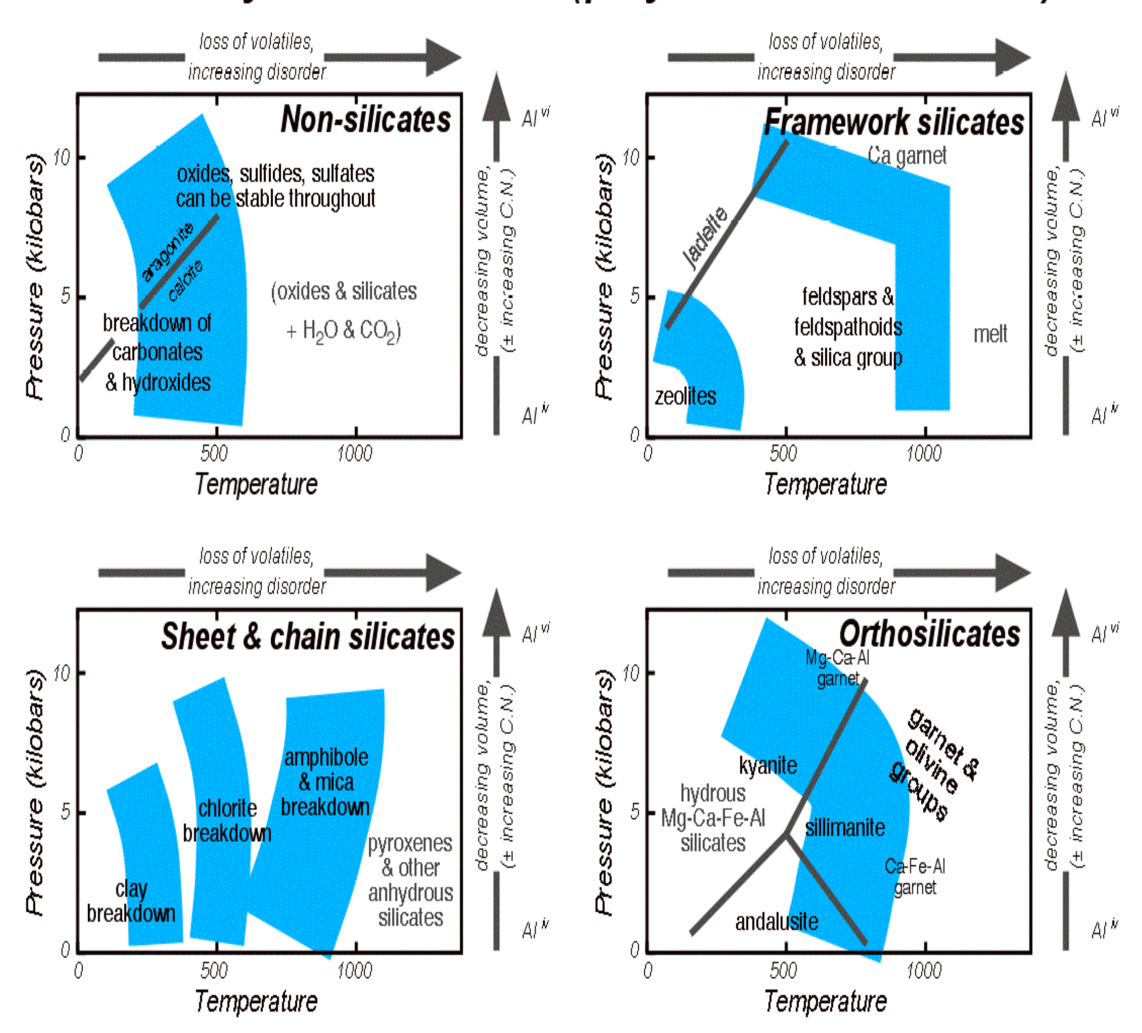
Mineral stability in metamorphic rocks:

The stability of minerals in metamorphic rocks is summarized in the figures below. The key reactions are those that involve:

1. Loss of volatile constituents with increasing temperature (dehydration or decarbonation reactions), or

2. Increase in density with pressure (commonly with an increase in coordination number of Al and/or other cations).

Generalized Pressure-Temperature Stability of Minerals (physical conditions)

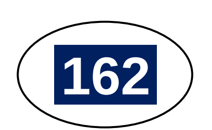


Principles governing mineral assemblages:

Equilibrium metamorphic mineral assemblages represent the stable set of minerals under any particular set of conditions (pressure, temperature, composition of solids and fluids). As we have seen already, metamorphic rocks can have an exceptionally wide range of possible bulk compositions from peridotites to rhyolites from carbonate to mud to quartzite.

What rules, beyond the principles above, govern the number and identity of minerals in metamorphic rocks?

1. The aggregate composition of the minerals must equal that of the rock. In other words, we can predict what minerals might be present by their compositional compatibility with each other and with the bulk composition of the rock.



2. Only a limited number of minerals can be present at equilibrium. In the general case over a range of P and T the number of minerals does not exceed the number of chemical constituents needed to describe the rock's composition.

Point 2 is a qualitative statement of the *mineralogical phase rule* (more next semester) which states that the number of phases (minerals) "P" present is less than or equal to the number of chemical components "C".

P C.

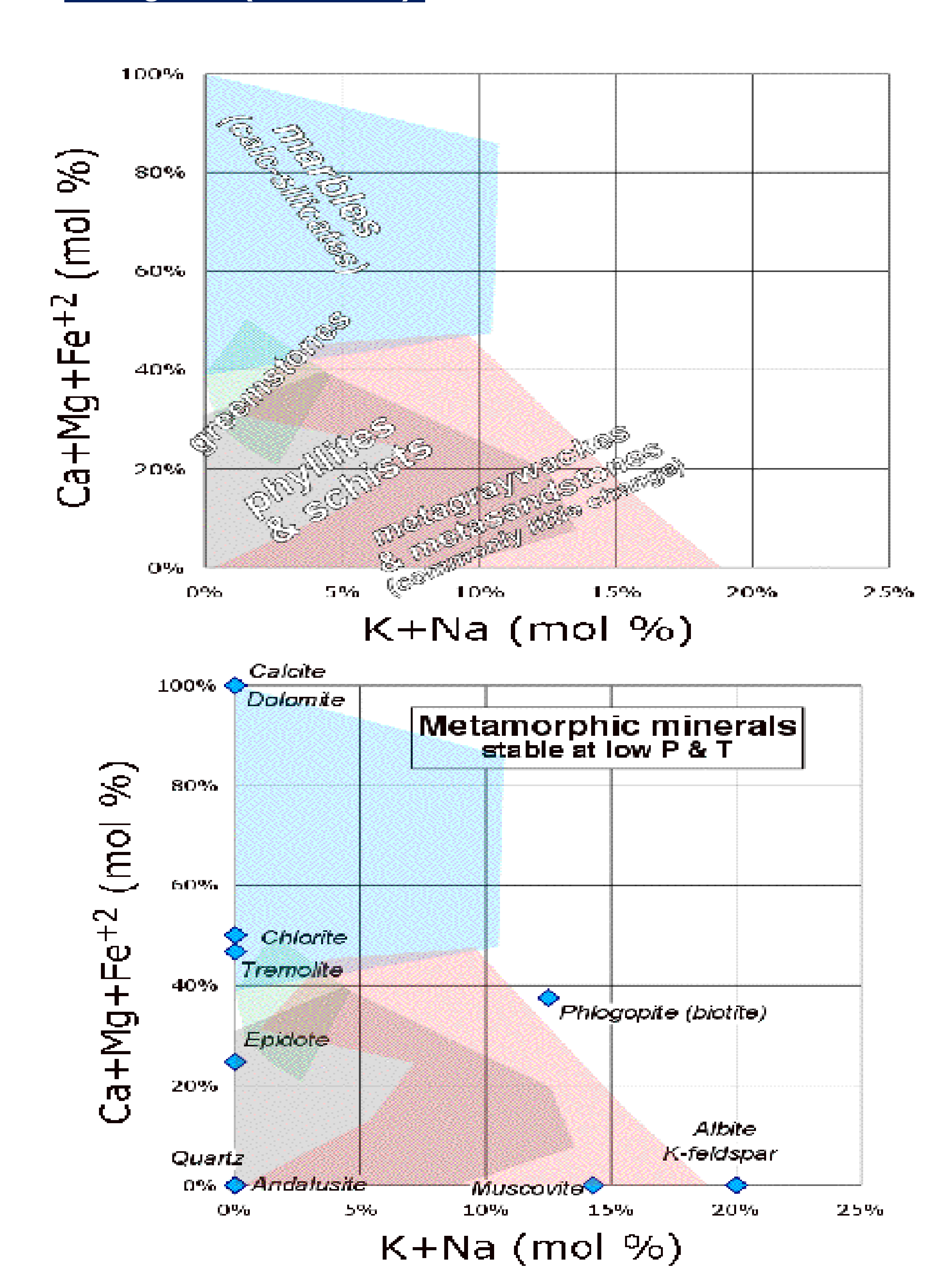
This rule follows directly from thinking about the conditions of stability (minimum) and will be illustrated on the board using our familiar energy diagrams for two (and three) components. In cases where elements substitute in solid solution (e.g., Mg for Fe or Na for K) they can be considered to act in place of one another and reduce the number of effective chemical components (formally, one introduces the concept of degrees of freedom we won't deal with that in this class).

This principle is quite helpful to use when looking at rocks and at diagrams like those below. It tells us:

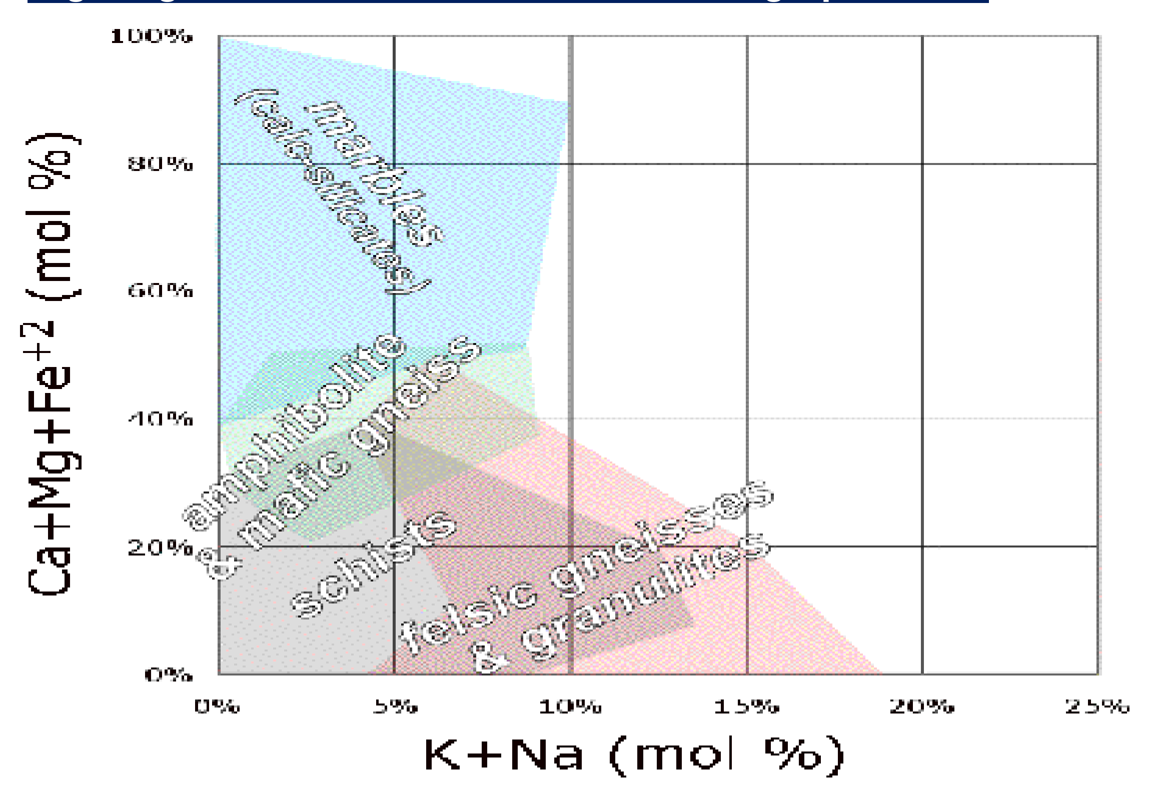
(a) that only a limited number of minerals can be in equilibrium in the same rock,

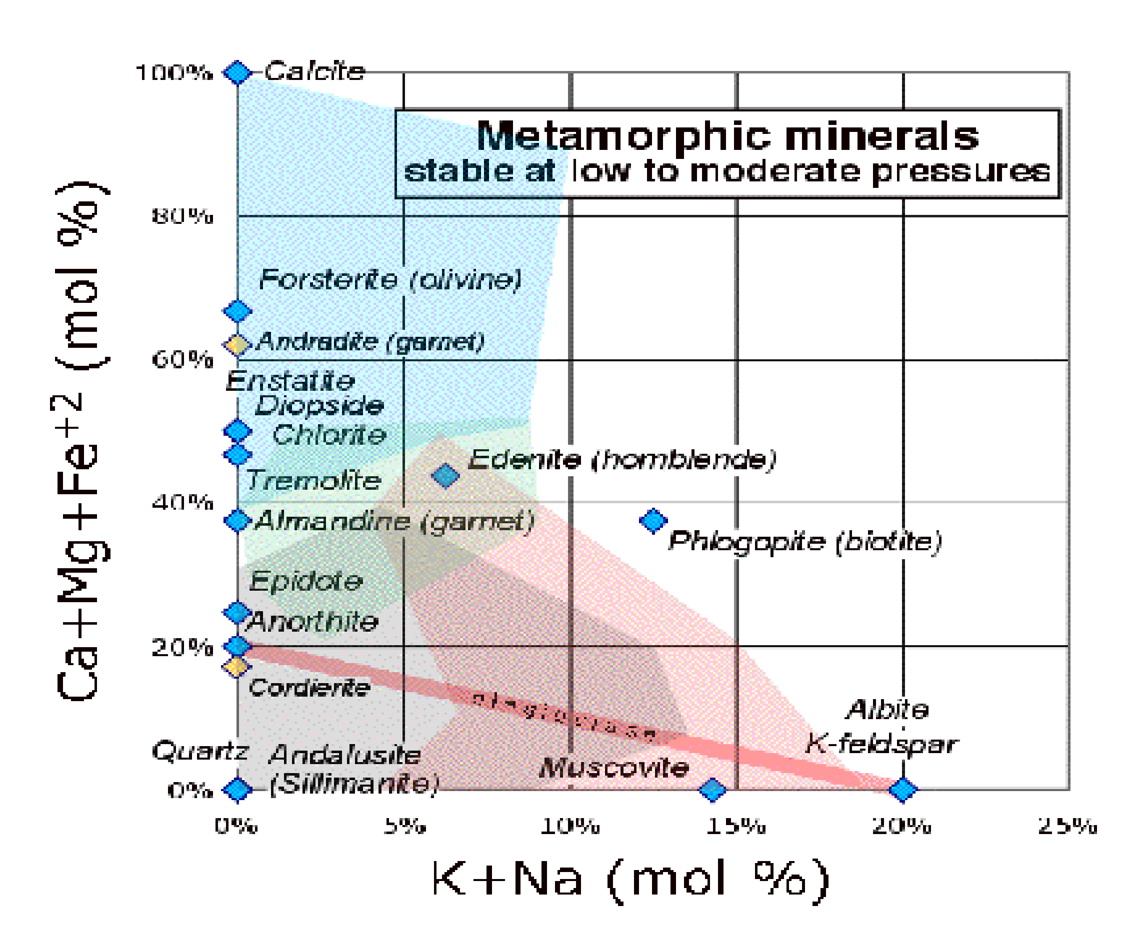
(b) that combinations of these minerals can not overlap with one another.

Low-grade (low T & P):



Higher grade associations from low- to high-pressure:





CHAPTER 9

Metamorphism of Pelitic Sediments

Pelitic Rocks:

What is the Metapelites?

- **Metapelites** are metamorphic rocks, which derived from contact or regional metamorphism of shale or mudstones (clay rich sediments).

- **Metapelites** are the most distinguished family in metamorphic rocks because the clays are very sensitive to variations in temperature and pressure, undergoing extensive changes in mineralogy during progressive metamorphism.

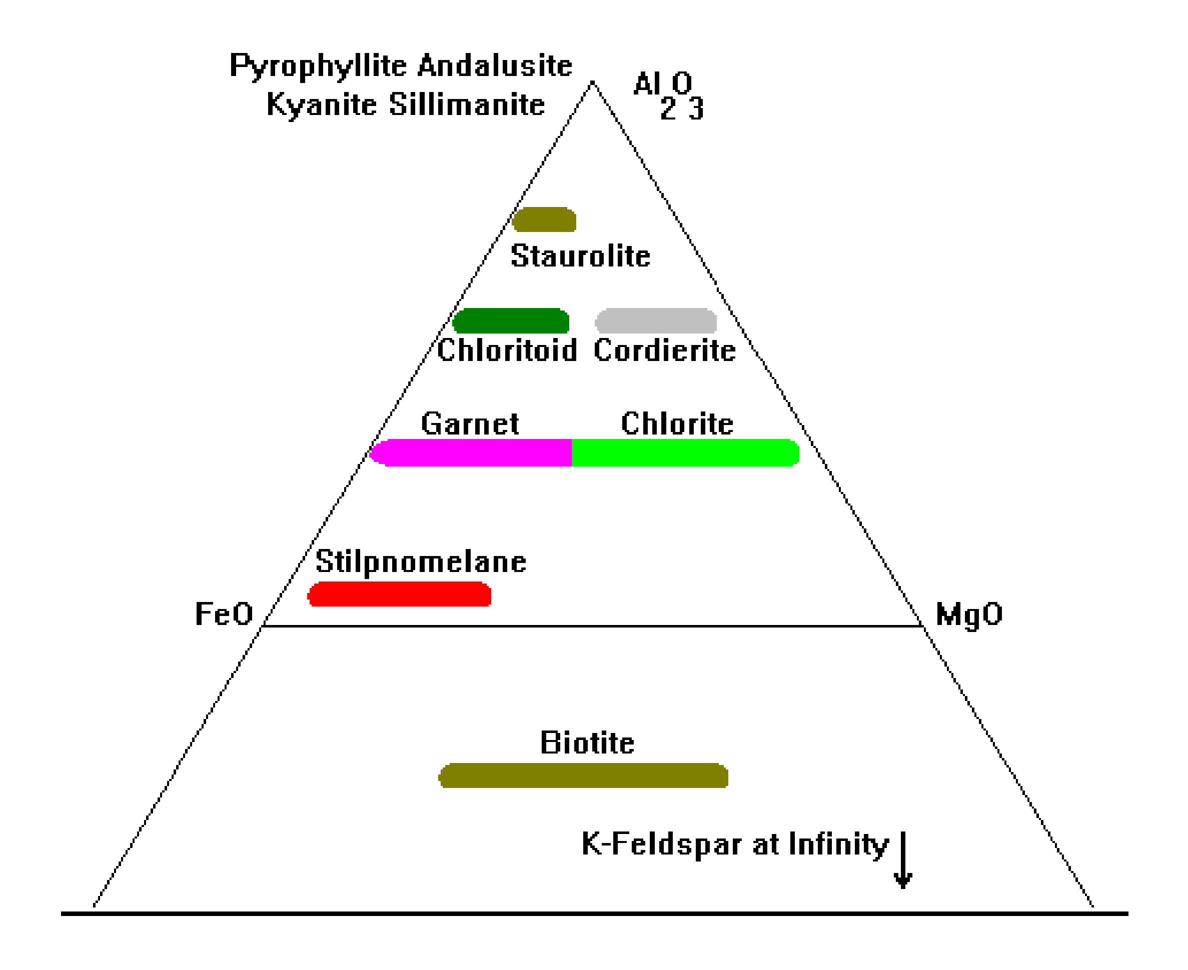
- **Pelitic sediments** are mineralogy dominated by fine Al-K-rich phyllosilicates (50 vol%), such as clays (montmorillonite, kaolinite, or smectite), fine white micas (sericite, paragonite, or phengite) and chlorite, all of which may occur as detrital or authigenic grains (10-30%).

- **Chemically, the pelitic rocks** are rich in Al_2O_3 and SiO_2, Na_2O, K_2O, and poor in CaO, therefore, the yielded metamorphic minerals during progressive metamorphism will be rich in Al_2O_3.

Mineralogy of metapelites:

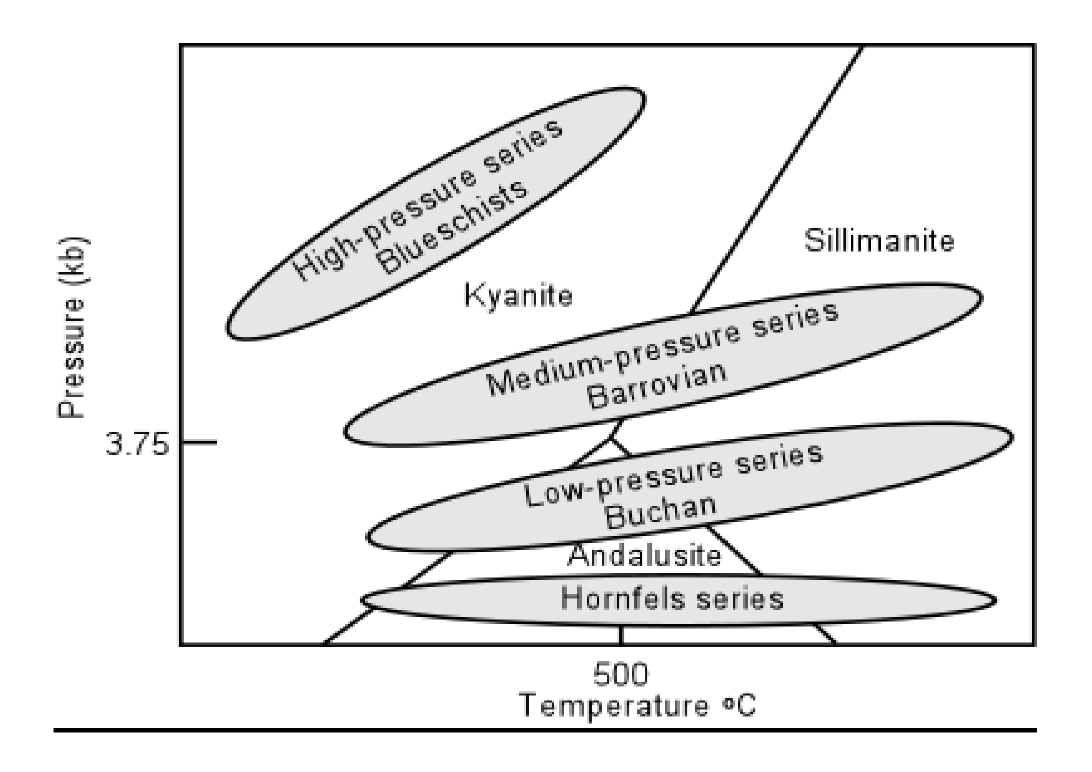
Metapelites contain the following mineral assemblage:

- Mica (Muscovite, biotite), pyrophyllite, chlorite, chloritoid.
- Feldspars (plagioclase and K-feldspars) .
- Garnet, staurolite, cordierite.
- Al-silicate (andalusite, Kyanite, and sillimanite).
- Quartz, orthopyroxene, spinel .



The metapelites will discuss their metamorphism in the following connditions:

- **Pre-metamorphic – low-grade metamorphic conditions.**
- **In Middle Pressure metamorphism (Barrovian zonal scheme).**
- **In the low pressure metamorphism (Buchan zonal scheme).**
- **In the high temperature conditions.**



1- Pre-metamorphic – low grade metamorphic changes:

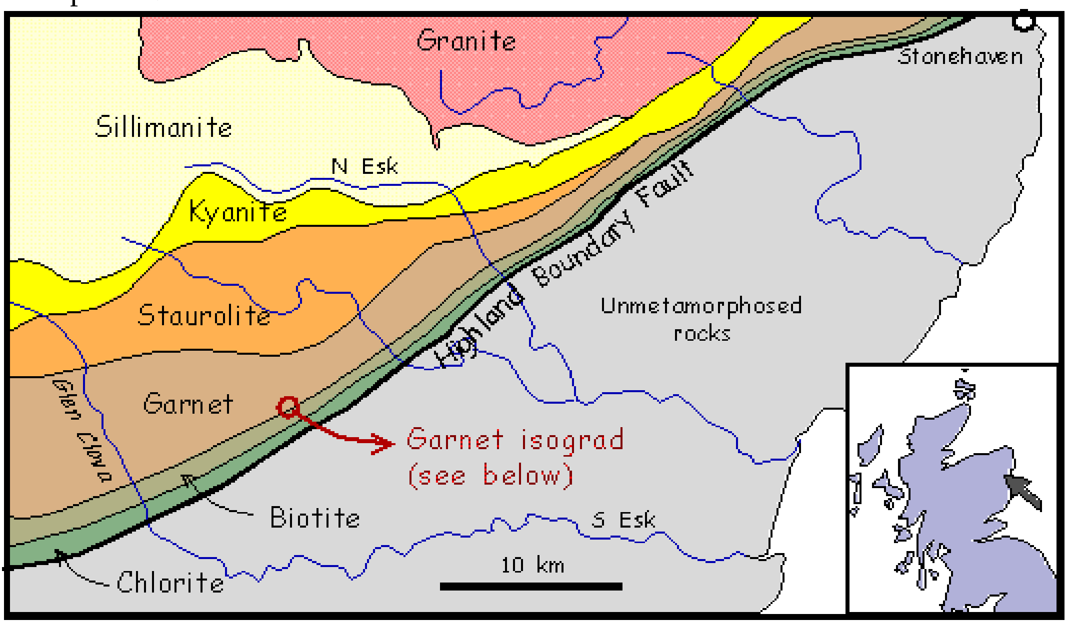
During compaction and diagenesis, changes in mudstones and shale include:

- Reducing of porosity (> 50 Vol.%) during burial & compaction.
- Original clay, smectite, are replaced by mixture of chlorite and illite (sericitic muscovite).
- With progress increase of P-T condition the following assemblage could be formed.
- chlorite + illite + kaolinite .
- chlorite + sericite + pyrophyllite + illite + koalinite .
- Illite crystallinity, as deined from XRD, used to measure the degree of diagenetic and very-low metamorphism.
- There is no sharp contact between diagenesis and low-Temperature metamorphism.

2 -Medium Pressures metamorphism :

Barrovian Zonal Scheme (MP metamorphism):

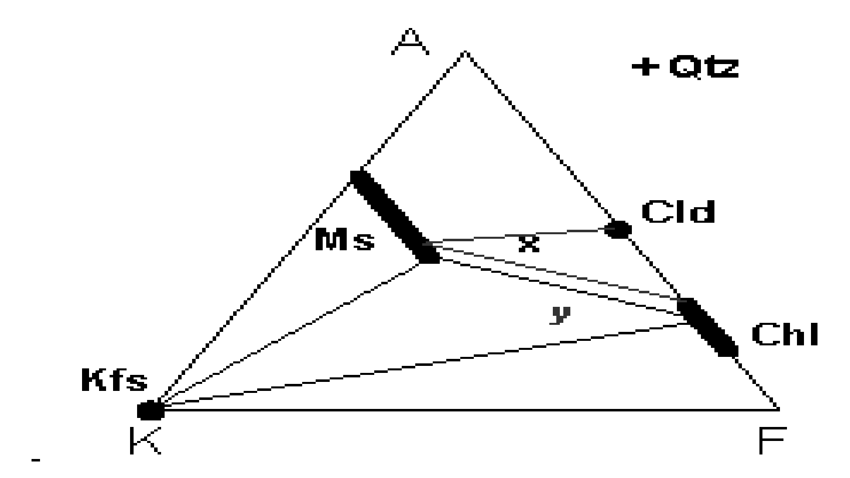
The classical zones of metamorphism in the Scottish Highlands and many other parts of the world include six distinct mineral assemblages that occur in the metapelites.



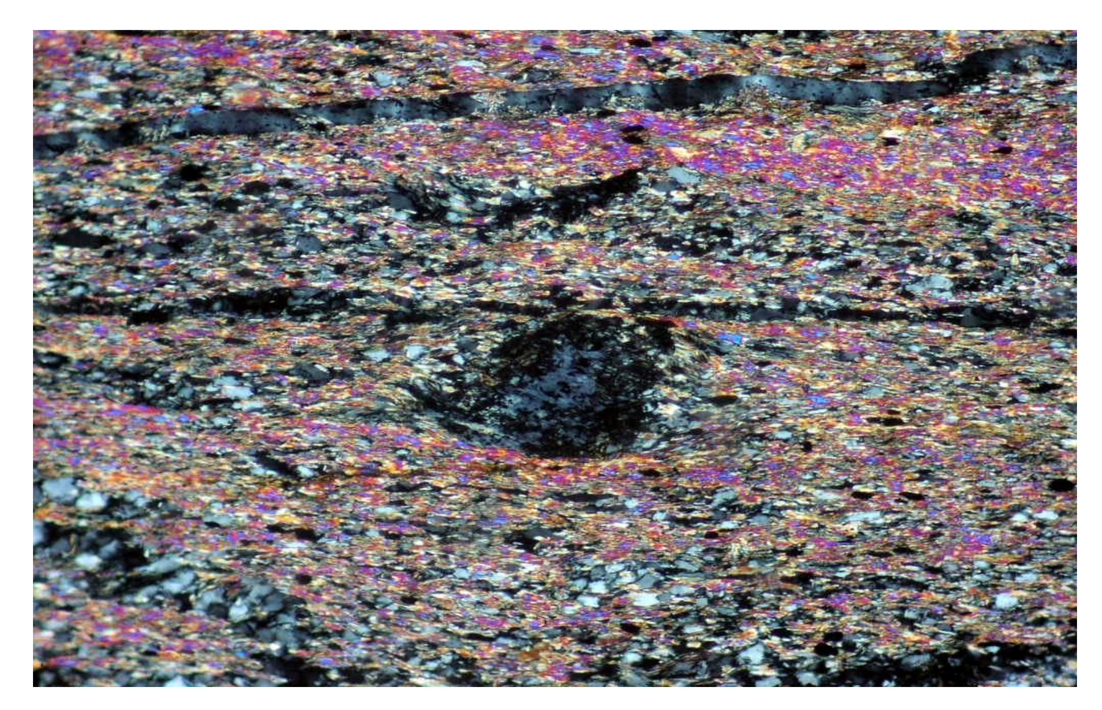
Metamorphic mineral zones in NE Scotland, after Barrow and Tilley

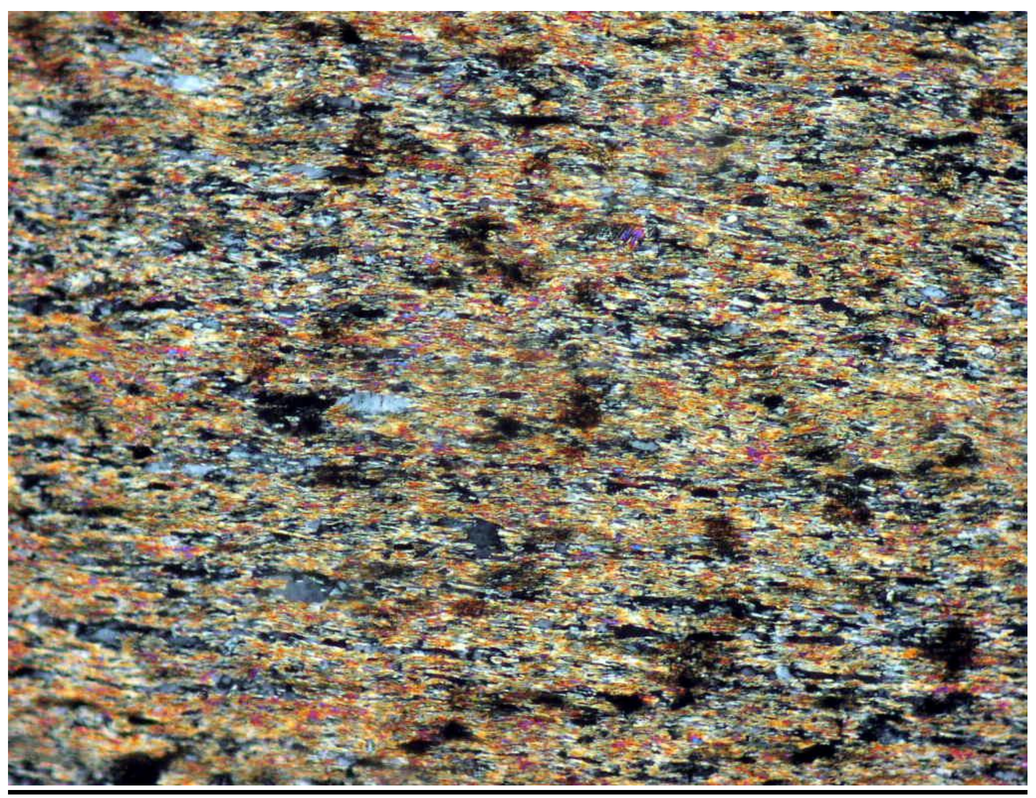
I- Chlorite zone:

- Metapelites of the chlorite zone are very fine-grained slates, so it makes difficult to investigate under the microscope,
- They tyically contain mineral assemblage: chlorite + Mg-Fe-bearing muscovite (phengitic) + quartz + Na-plagioclase (albite) ± K-feldspars ± stilpnomelane ± calcite.



-





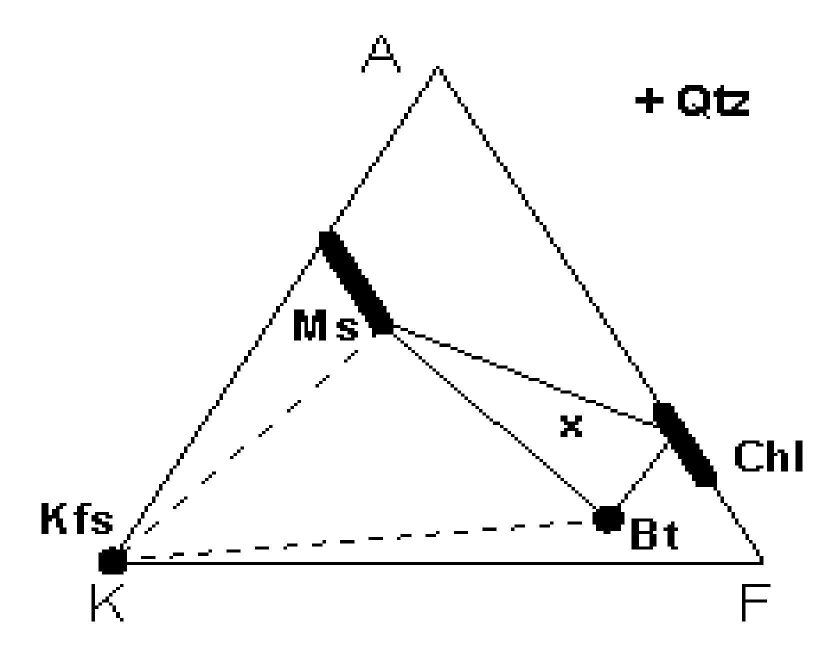
II- Biotite zone:

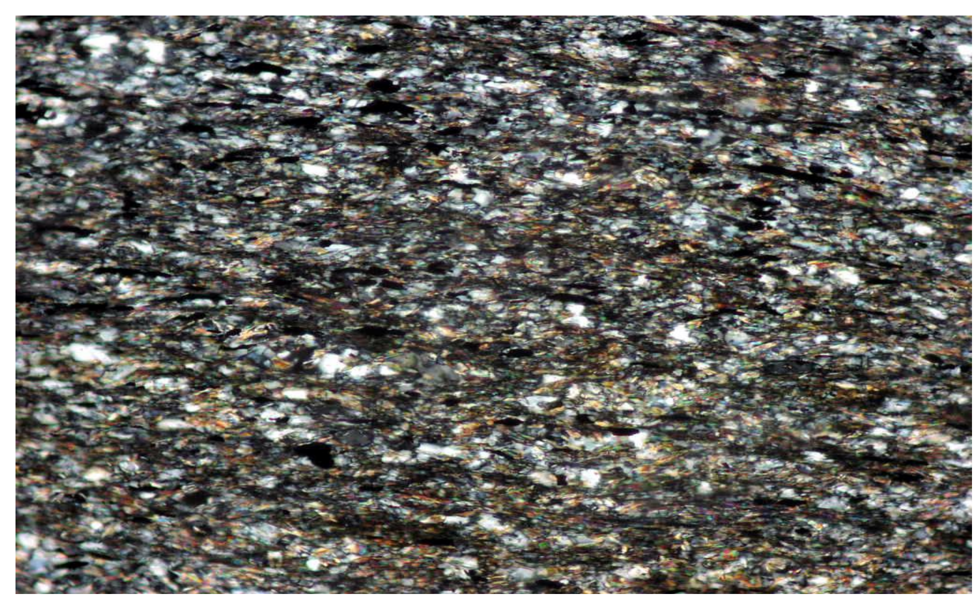
- Metapelites of the biotite zone are defined by first appearance of biotite through one of two mineral reactions (depending upon the presence or absence of K –feldspar):

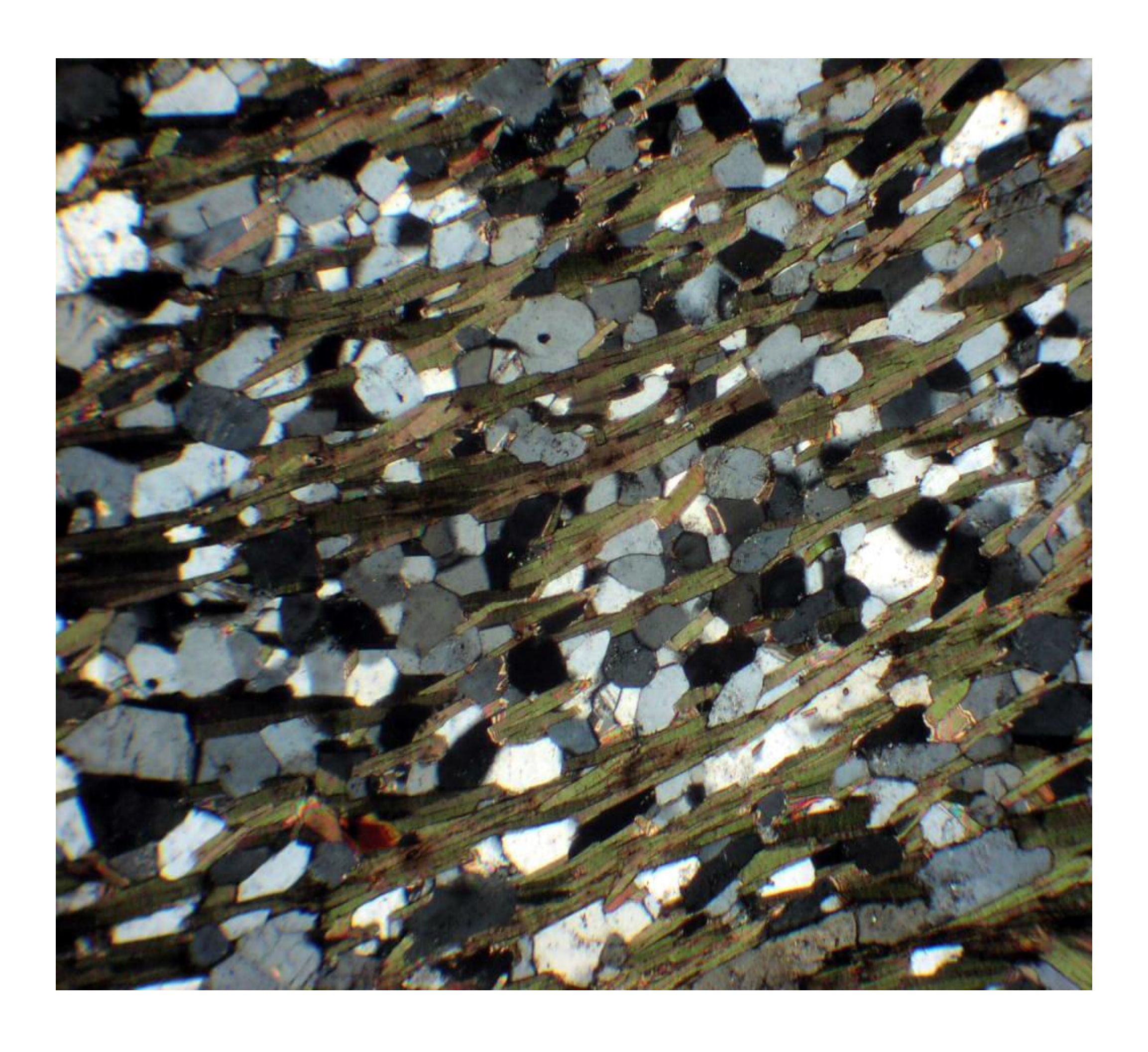
  K-feldspar + chlorite ➔ biotite + muscovite + quartz + H_2O

  Phengitic Ms + chlorite ➔ biotite + phengitic-poor Ms + quartz + H_2O

- They are typically Phyllite and contain mineral assemblage: chlorite + muscovite + biotite + quartz + Na-plagioclase (albite) ± calcite.





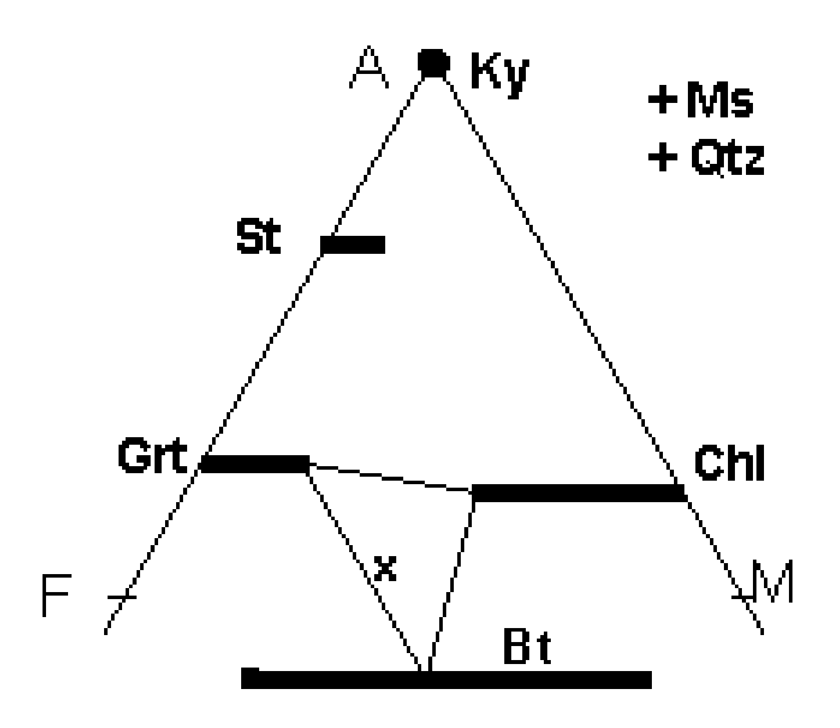


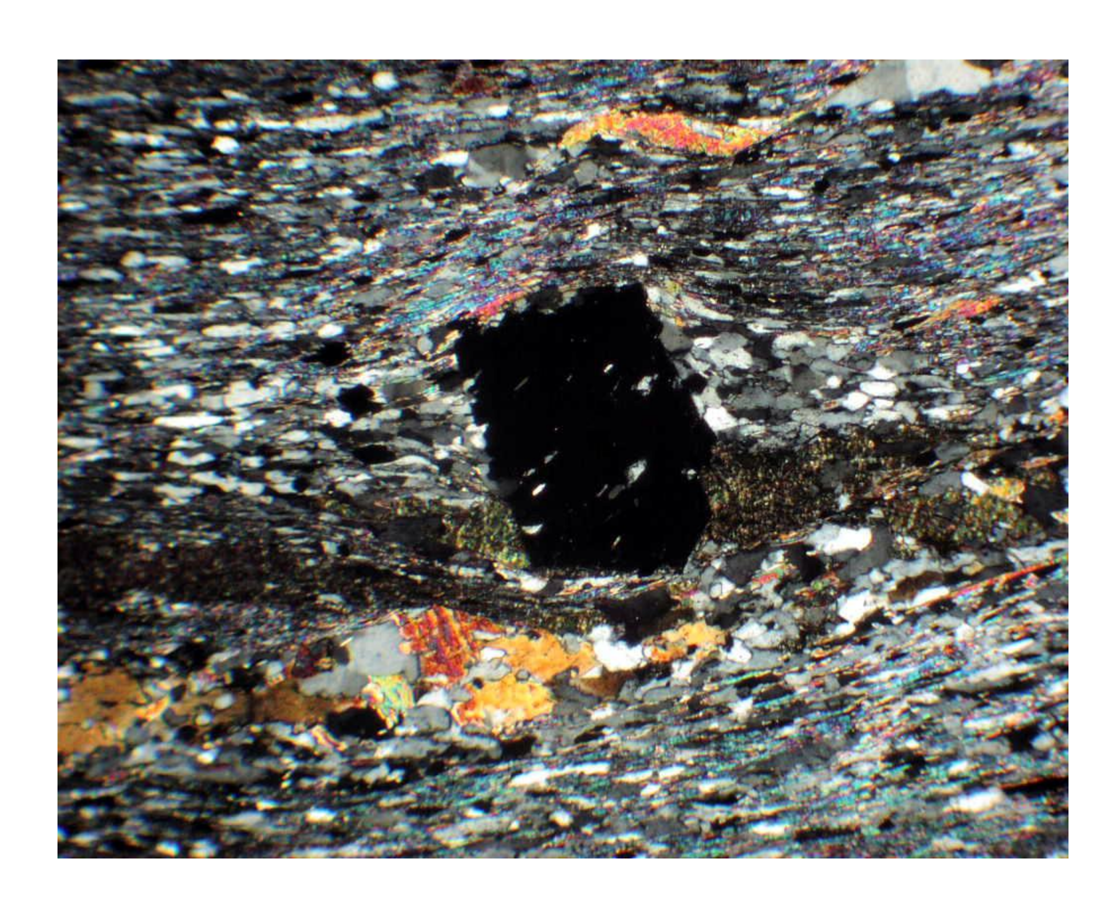
III- Garnet zone:

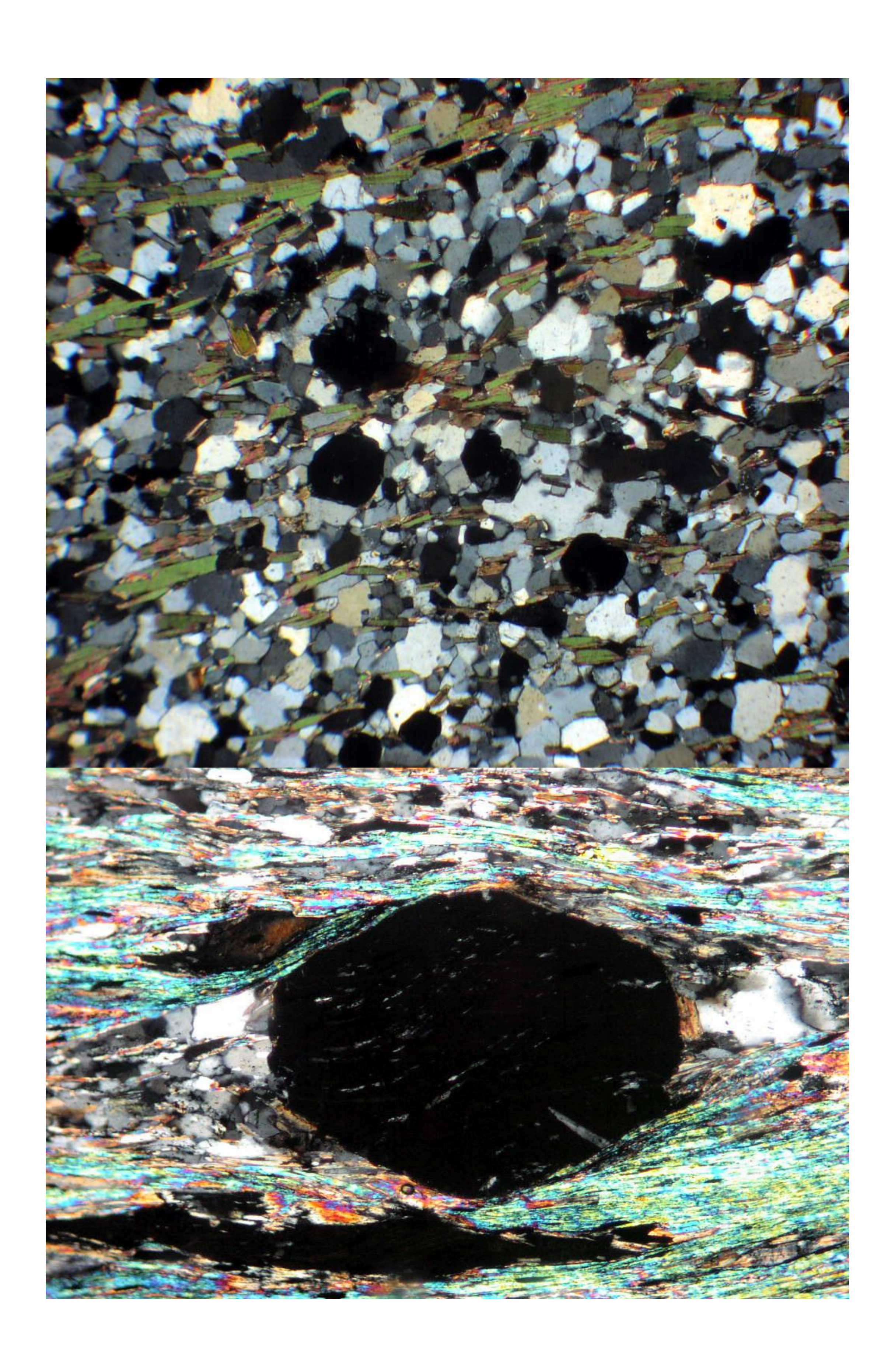
- Metapelites of the garnet zone are defined by first appearance of garnet porphyroblasts (Fe-rich almandine) through the following mineral reaction:

  Chlorite + muscovite ➔ garnet + biotite + quartz + H_2O

- They are typically medium to coarse grained schists and contain mineral assemblage: garnet + biotite + chlorite + quartz + Na-plagioclase (albite) ± epidote.


A
Ky
+ Ms
+ Qtz
St
Grt
Chl
x
F
M
Bt





IV- Staurolite zone:

- Staurolite is only form in Al-rich, Ca-poor pelites. This will depend on the stability of plagioclase, which allow available Ca to combined Al. Therefore, Al is reduced and other Al-silicate minerals does not form.

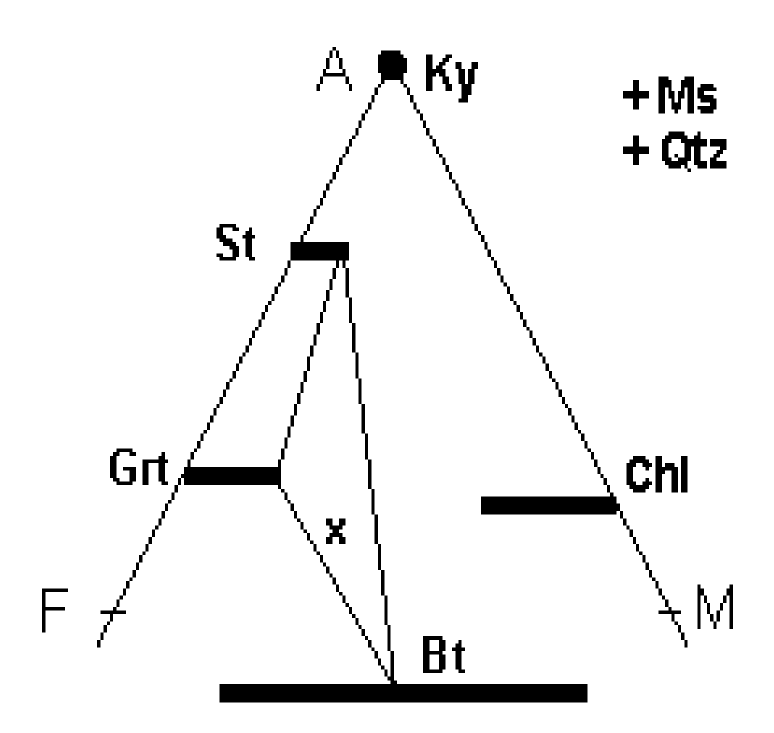
- staurolite forming through the following mineral reaction:

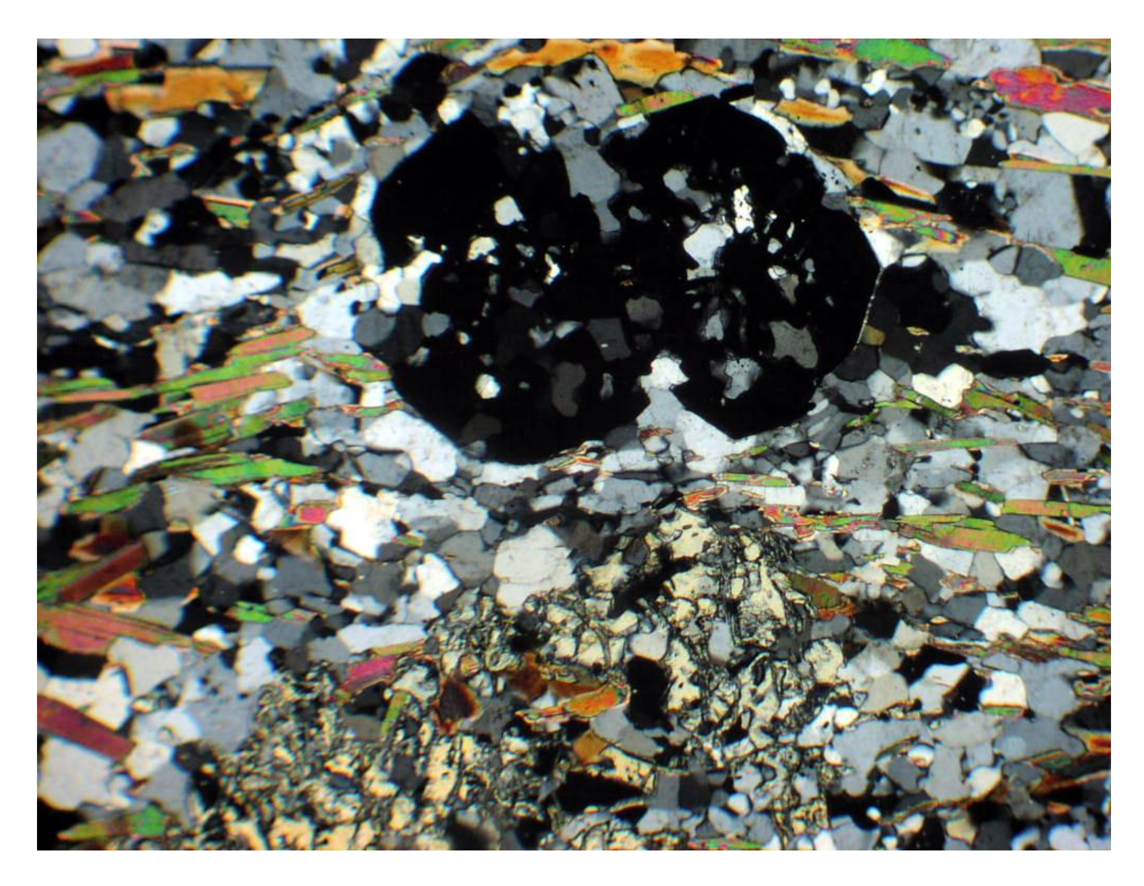
Chld + Qtz ➔ St + Grt + H_2O

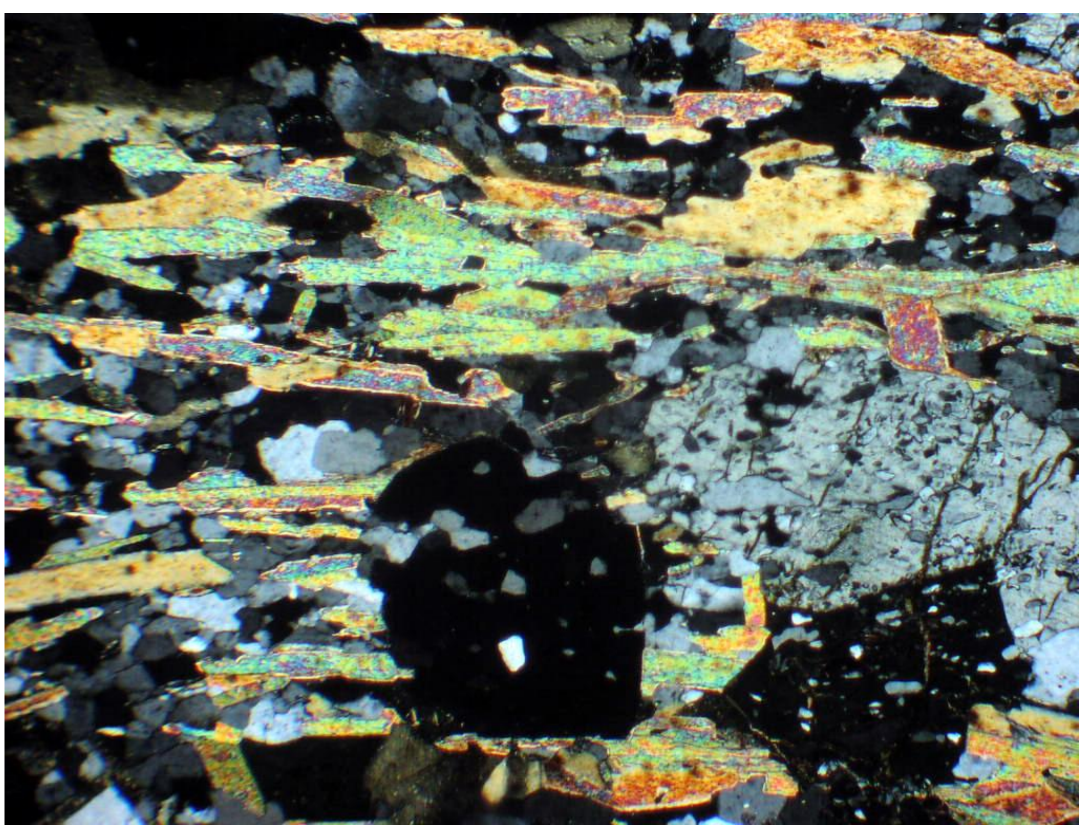
Grt + Ms + Chl ➔ St + Bt + Qtz + H_2O (Grt consuming reaction)

Ms + Chl ➔ St + Bt + Qtz + H_2O

They are typically medium to coarse grained schists and contain mineral assemblage: staurolite + garnet + biotite + muscovite + quartz + plagioclase ± chlorite (retrograde).







V- Kyanite zone:

- Kyanite zone is typified by the range of the assemblages:

Ky + St + Bt + Ms + Qtz,
Ky + Grt + Bt + Ms + Qtz,

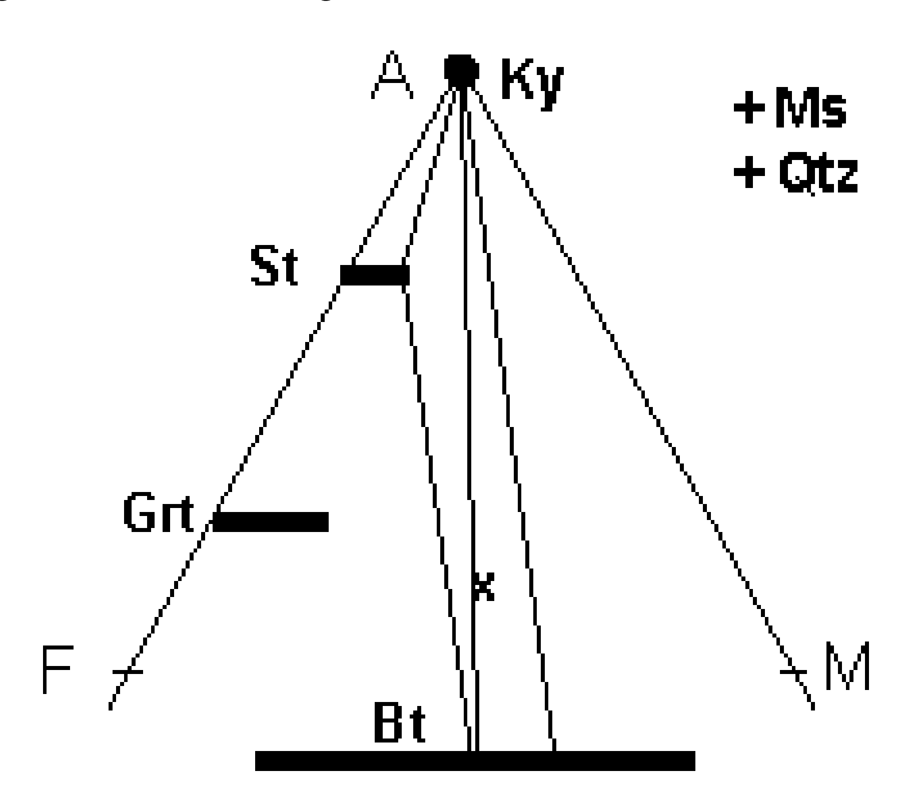
Ky + Grt + St + Bt + Ms + Qtz,
Ky + Bt + Ms + Qtz

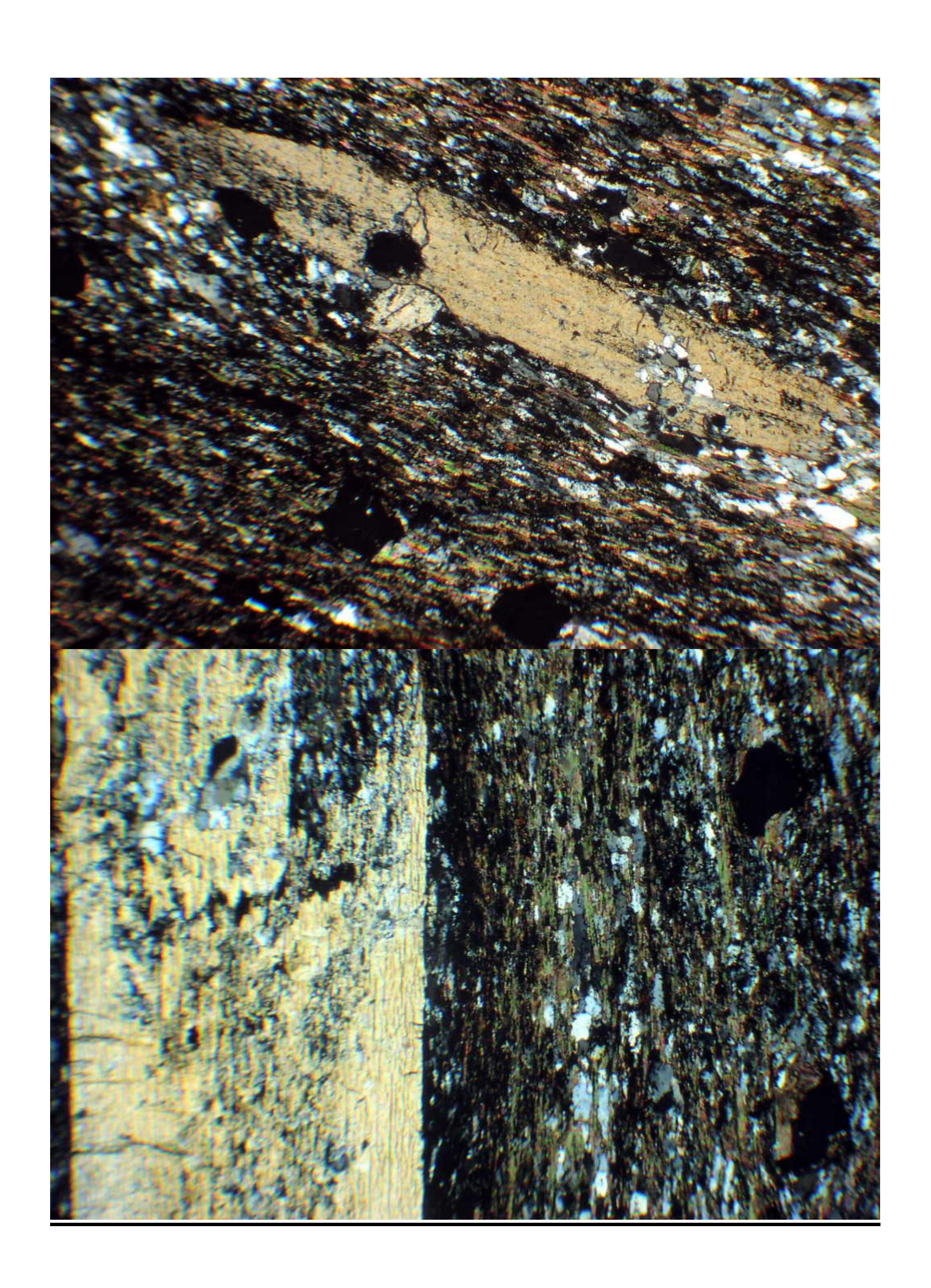
- Kyanite formed through the reaction:

Ms + St + Chl ➔ Ky + Bt + Qtz + H_2O

Ms + St + Qtz ➔ Ky + Bt + H_2O

They are typically coarse grained schists and contain above mentioned diagnostic mineral assemblage.





V- Sillimanite zone:

- this zone is the highest zone in the Barrovian series

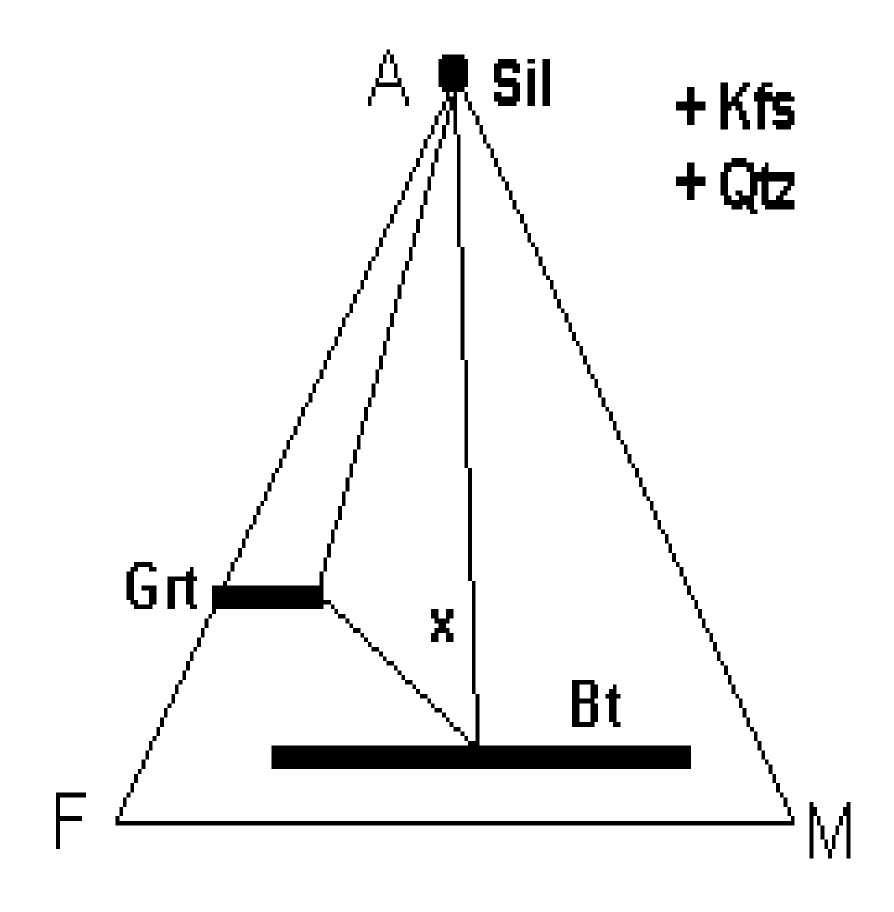
- It characterize by presence of Sillimanite in the form of fibrolite, and/or coarse prismatic crystals. It could form as Psedudomorph of andalusite via solid-solid reaction And ⇔ Sill

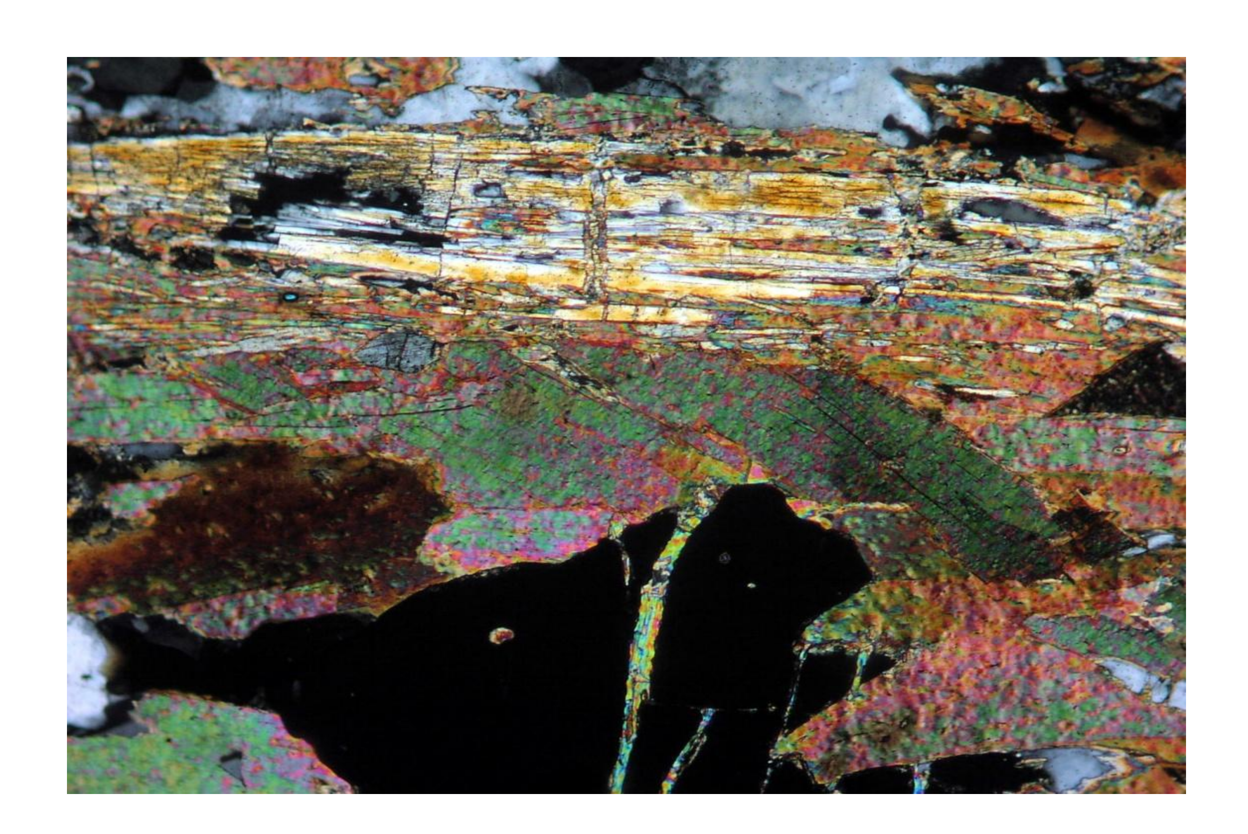
- Sillimanite coud also formed as a result of the following reaction:

St + Ms + Qtz → Grt + Bt + Sill+ H_2O

Ms + St + Chl → Bt + Sill+ H_2O

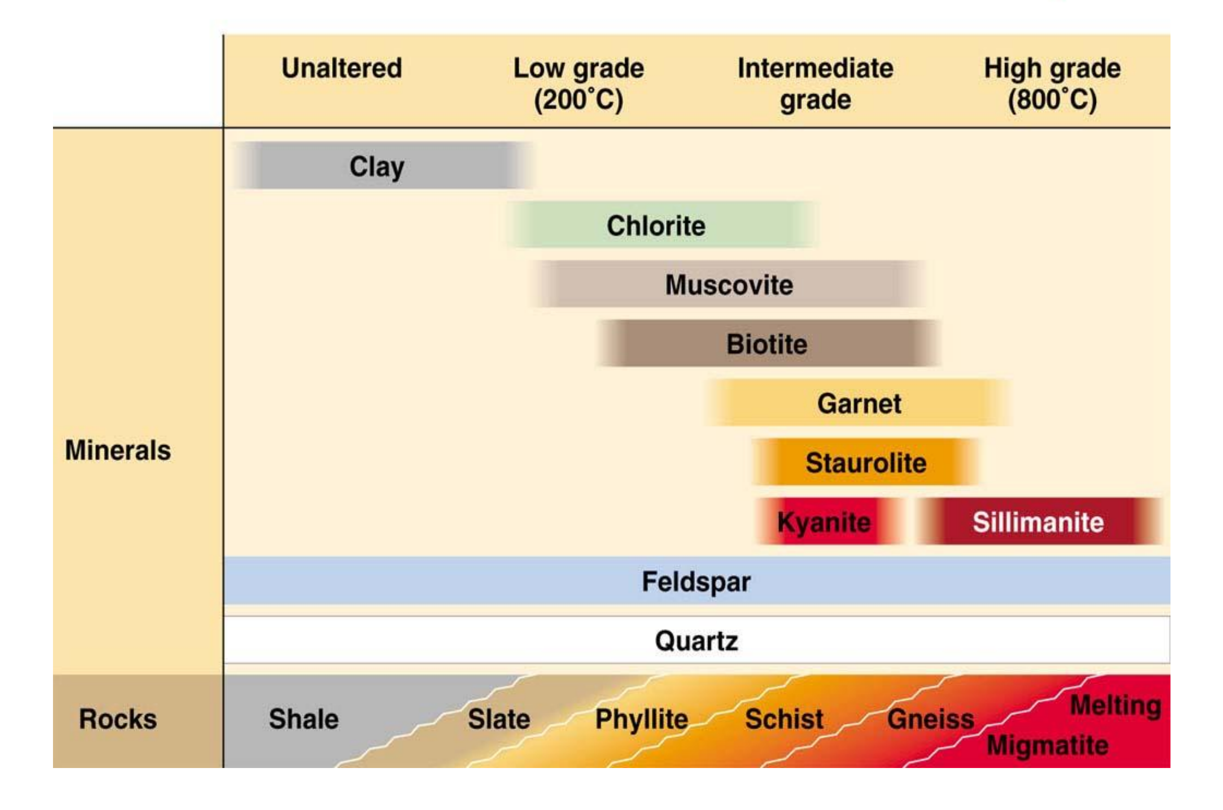
They are typically coarse grained schists/gneisses and contain mineral assemblage of Sill ± St + Grt + Bt + Ms + Qtz + Pl ± Ky.

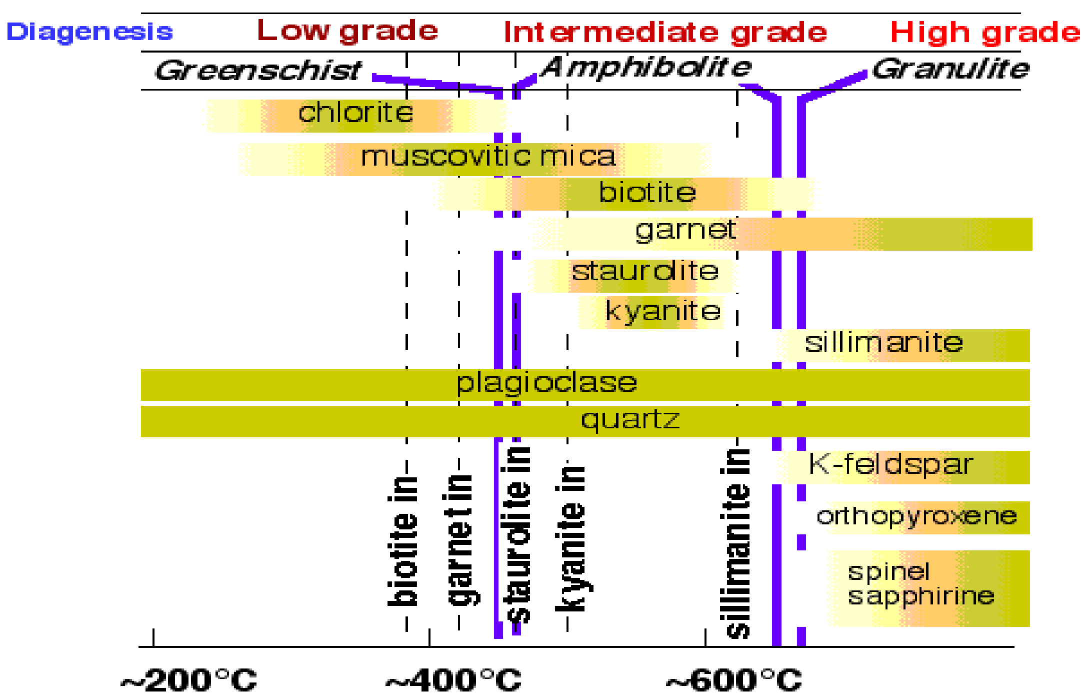




Stability of metamorphic:

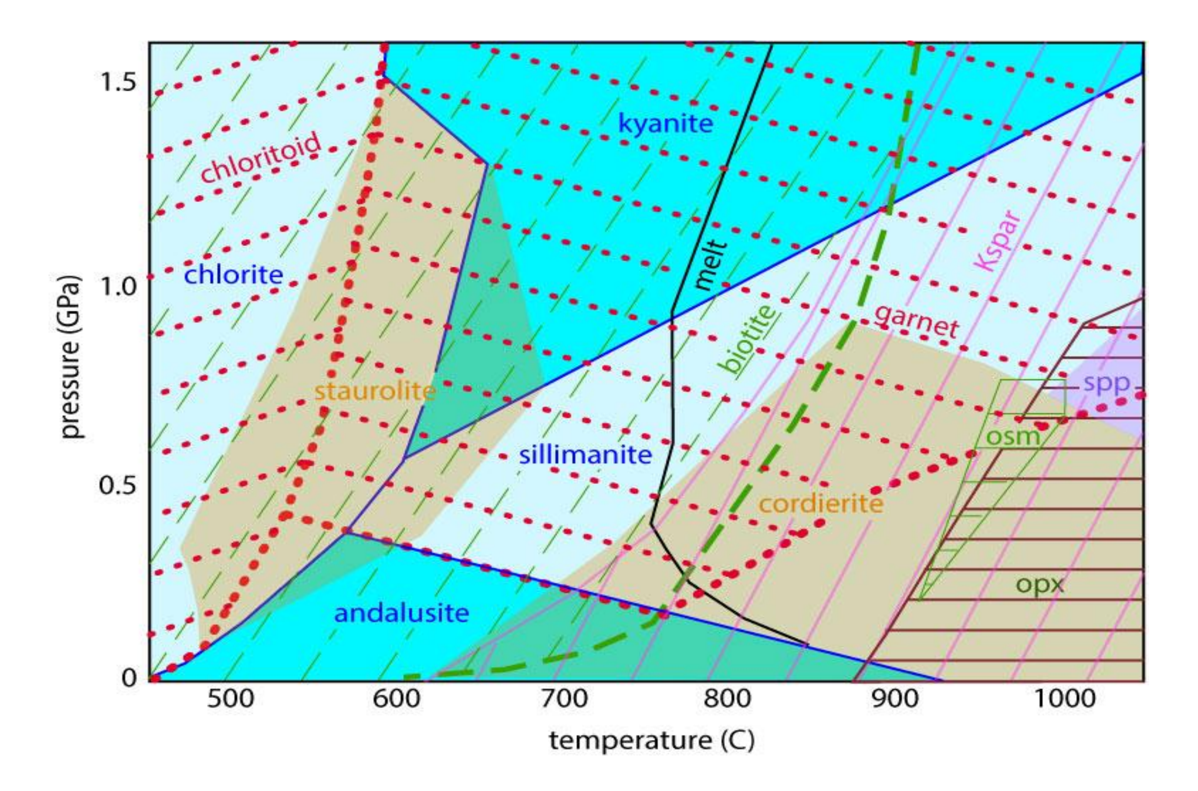
	Metamorphic Zones					
	Chlorite	Biotite	Garnet	Staurolite	Kyanite	Sillimanite
Chlorite						
Muscovite						
Biotite						
Garnet						
Staurolite						
Kyanite						
Sillimanite						
Plagioclase						
Quartz						





The protoliths for **pelitic rocks** are shales (aluminous rocks), not sandstones (quartzofeldspathic rocks). Here are the stability fields of common pelitic minerals:

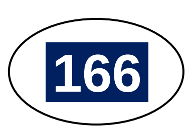


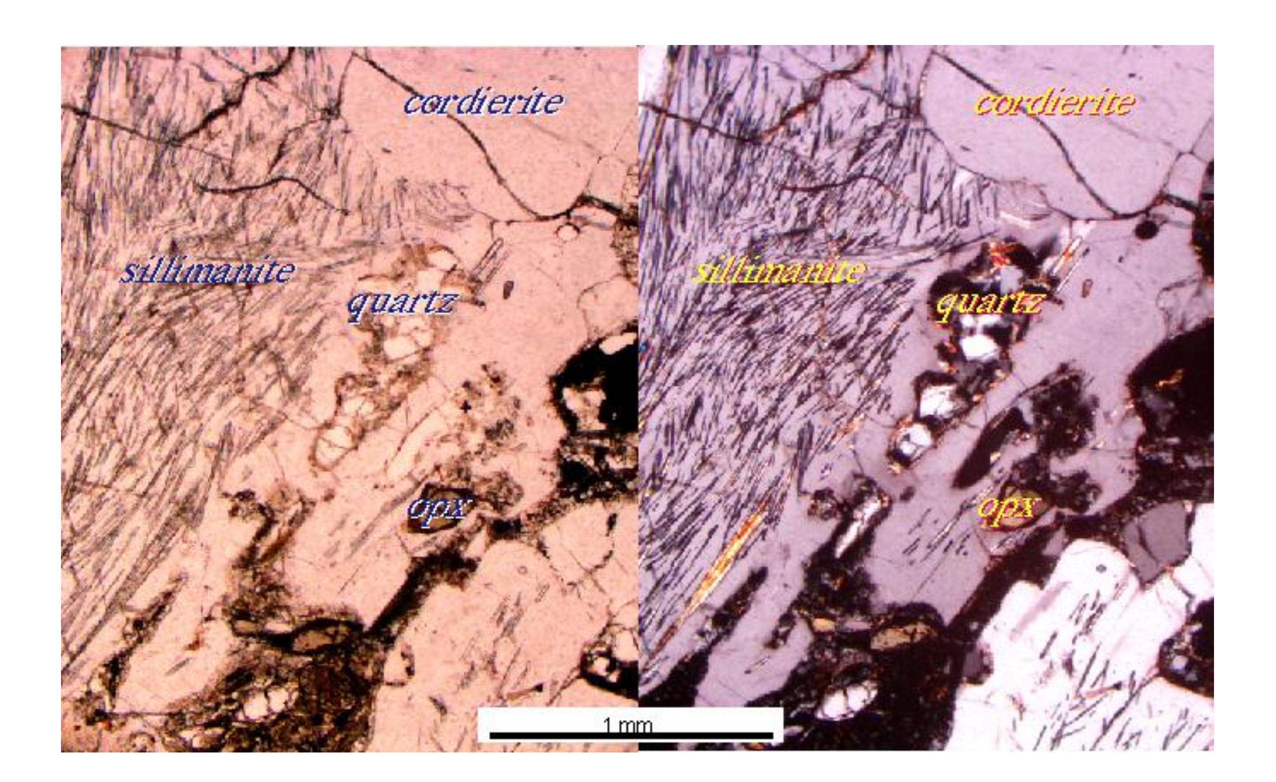


the presence of:

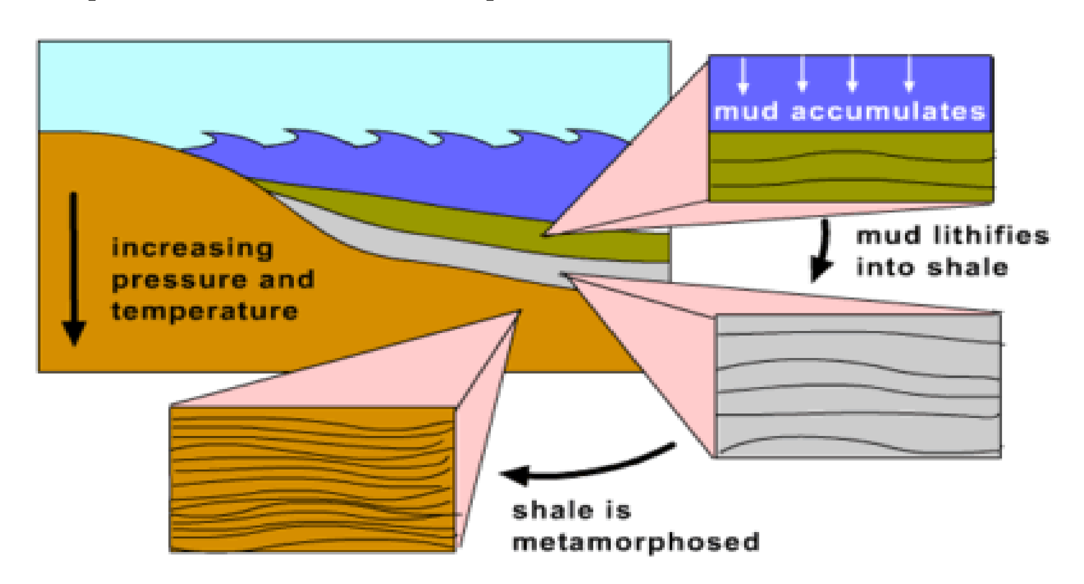
andalusite $^{VI}Al^{V}AlSiO_5$ implies low P metamorphism.
kyanite $^{VI}Al^{VI}AlSiO_5$ implies high P .
sillimanite $^{VI}Al^{IV}AlSiO_5$ implies high T. Sillimanite first grows as **fibrolite**, a fine-grained acicular form.

chlorite $MgFeAlSiO(OH)_x$ implies low T.
biotite $K(Mg,Fe)AlSi_3O_{10}(OH)_2$ implies moderate T.
garnet implies moderate T .
staurolite $MgFeAlSiO(OH)_x$ implies moderate-high P .
chloritoid $MgFeAlSiO(OH)_x$ implies moderate-high P .
cordierite $MgFeAlSiO(OH)_x$ implies low P .
paragonite $NaAlSi_3O_{10}(OH)_2$ implies high P.





Metamorphism is difficult to understand because there are many combinations of temperature and pressure that can create rocks. For example, mud and clay quietly settle on the ocean floor. As more mud and clay settle on top of it, the weight of the sediments "squeezes" the water from the mud and clay on the bottom. It becomes cemented together by chemical interactions and it becomes a sedimentary rock called **shale**. The shale is put under moderate pressure and low temperature due to burial or plate movements. The new pressure and temperatures changed the chemical make up of the shale into the metamorphic rock called **slate**.



Pelitic rocks or mudy rocks: give by increase in grade of metamorphism the following rocks: Slate then phyllite then schist then gneiss and if partial melting occurs give migmatite.

The slate has even dull planes but **phyllite** have shiny planes. **Shist** have irregular planes but gneiss not broken easily.

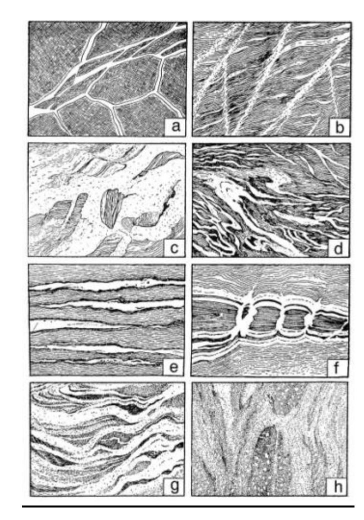
Migmatite composed of black or melanosome layers rich in biotite but its leucosome or light layers are K-rich minerals as microcline and quartz.

The migmatite is may be formed by three reasons:

1- Lit par lit injection from the neighboring granitic magma but this is limited in the field and their layer composed of low grade melanosome or schist or phyllite alternate with granitic leucosome with the same composition of the granitic rocks in contact. The chemical composition of both leucosome and melanosome differ than the chemical composition of the muds.

2- **Migmatite formed by partial melting of pelitic protolith** in regionally metamorphosed terrain. Here we can trace it for several kilometers in the field and chemical composition of their melanosome + leucosome is similar to its pelitic protolith.

3- Migmatite formed by metasomatic addition of Na, K and silica from solution on banded sedimentary rocks give granitic layers. In this case the migmatite composition is differing than pelitic rocks.

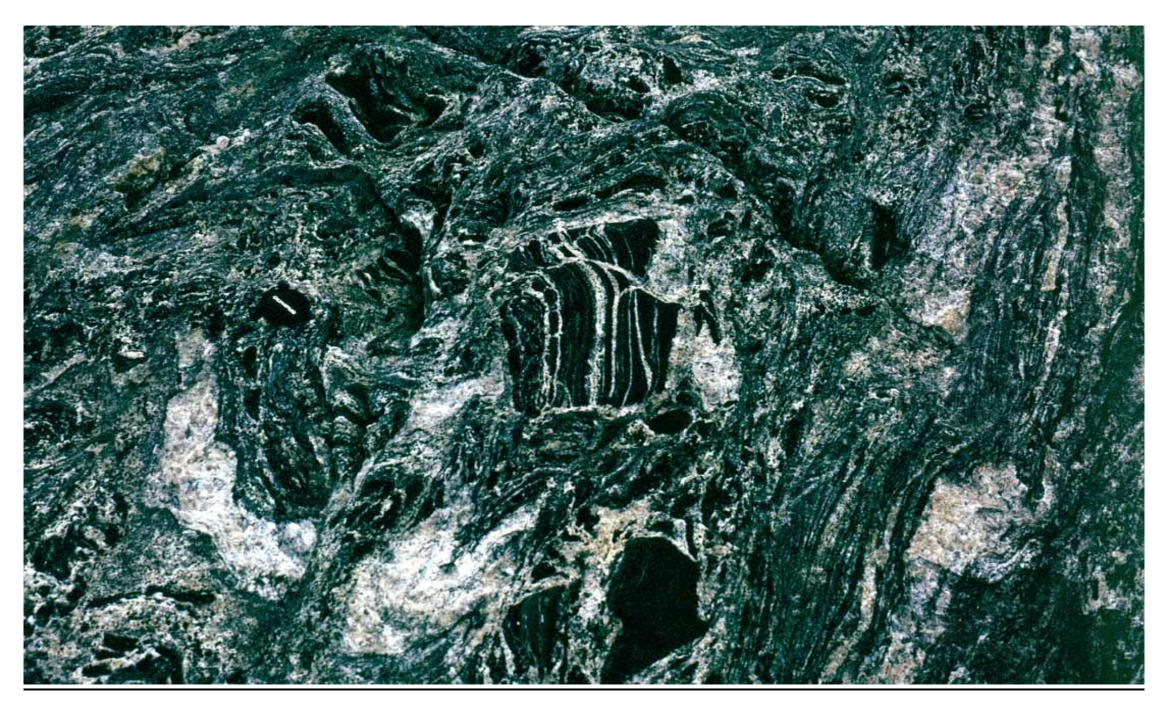


Some textures of migmatites**. a. Breccia structure** in agmatite. **. b. Net-like structure**.. **c. Raft-like structure**. **d. Vein structure. e. Stromatic, or layered, structure. f. Dilation structure** in a boudinaged layer**. g. Schleiren structure. h. Nebulitic structure**. From Mehnert (1968) *Migmatites and the Origin of Granitic Rocks*. Elsevier. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



Complex migmatite textures including multiple generations of concordant bands and cross-cutting veins. Angmagssalik area, E. Greenland. Outcrop width ca. 10 m. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.





More complex migmatite textures.

Metamorphism of Pelitic Sediments:

- **Mudstones and shales**: very fine grained mature clastic sediments derived from continental crust. Characteristically accumulate in distal portions of a wedge of sediment off the continental shelf/slope. Grade into coarser graywackes and sandy sediments toward the continental source. Although begin as humble mud, metapelites represent a distinguished family of metamorphic rocks, because the clays are very sensitive to variations in temperature and pressure, undergoing extensive changes in mineralogy during progressive metamorphism. The mineralogy of pelitic sediments is dominated by fine Al-K-rich phyllosilicates, such as clays (montmorillonite, kaolinite, or smectite), fine white micas (sericite, paragonite, or phengite) and chlorite, all of which may occur as detrital or authigenic grains. The phyllosilicates may compose more than 50% of the original sediment. Fine quartz constitutes another 10-30%. Other common constituents include feldspars (albite and K-feldspar), iron oxides and hydroxides, zeolites, carbonates, sulfides, and organic matter . Distinguishing chemical characteristics: high Al_2O_3 and K_2O, and low CaO. Reflect the high clay and mica content of the original sediment and lead to the dominance of muscovite and quartz throughout most of the range of metamorphism. High proportion of micas common development of foliated rocks, such as slates, phyllites, and mica schists. The chemical composition of pelites can be represented by the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (“KFMASH”). If we treat H_2O as mobile, the petrogenesis of pelites is represented well in AKF and A(K)F diagrams)..

Metamorphic Zones:

Barrovian metamorphic **zones** are defined by reactions that result in the appearance or disappearance of minerals and can be mapped as isograds •

chl —> bi —> gar —> st —> ky —> sill —> sill + or

Barrovian zone	mineral assemblage
chlorite zone	chlorite + mus + qtz + H_2O + relict minerals
biotite zone	chlorite + biotite + mus + qtz + H_2O
garnet zone	chlorite + biotite + garnet + mus + qtz + H_2O
staurolite zone	staurolite + 2 AKFM phases + mus + qtz + H_2O
kyanite zone	kyanite + 2 AKFM phases + mus + qtz + H_2O
sillimanite zone	garnet + biotite + sillimanite + mus + qtz + H_2O
2nd sillimanite zone or sillimanite + orthoclase zone	sill + or + qtz + H_2O + melt and **no mus**

Table 28-1. Chemical Compositions* of Shales and Metapelites

	1	2	3	4	5
SiO_2	64.7	64.0	61.5	65.9	56.3
TiO_2	0.80	0.81	0.87	0.92	1.05
Al_2O_3	17.0	18.1	18.6	19.1	20.2
MgO	2.82	2.85	3.81	2.30	3.23
FeO	5.69	7.03	10.0	6.86	8.38
MnO	0.25	0.10			0.18
CaO	3.50	1.54	0.81	0.17	1.59
Na_2O	1.13	1.64	1.46	0.85	1.86
K_2O	3.96	3.86	3.02	3.88	4.15
P_2O_5	0.15	0.15			
Total	100.00	100.08	100.07	99.98	96.94

* Reported on a volatile-free basis (normalized to 100%) to aid comparis

1. "North American Shale Composite". Gromet *et al.* (1984). **2.** Average of ~100 published shale and slate analyses (Ague, 1991). **3.** Ave. pelite-pelagic clay (Carmichael, 1989). **4.** Ave. of low-grade pelitic rocks, Littleton Fm, N.H. (Shaw, 1956). **5.** Ave. of

The *AKF* diagram

It is a projection from *plagioclase, alkali feldspar* and *quartz*. The three components are calculated as follows:

$(Al_2O_3 + Fe_2O_3) – (Na_2O + K_2O + CaO)$ **(A)**

K_2O **(K)**

$FeO + MgO + MnO$ **(F)**

Note that in calculation of the A component, we are interested in Al_2O_3 that occurs in excess of the amount tied-up in plagioclase and alkali feldspar. The positions of the most common AKF minerals and example of assemblages in the low-P 191amphibolites facies .

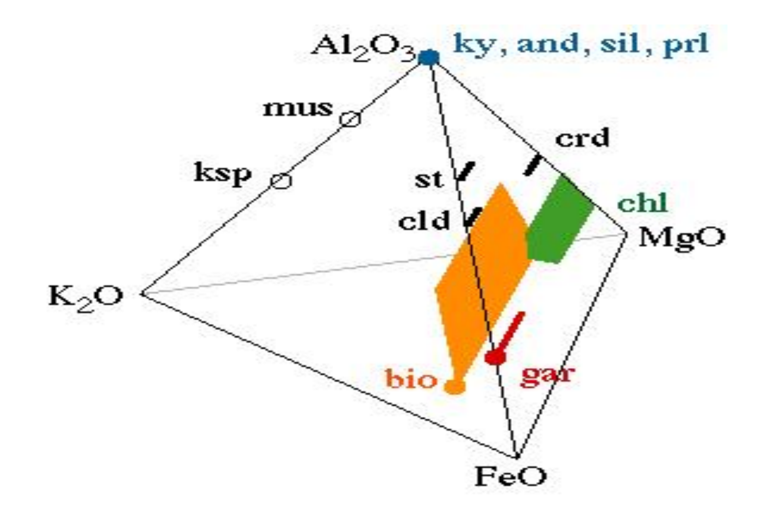
AFM (AKFM) diagram:

Mathematically, the AFM coordinates are calculated as follows:

(if projected from muscovite) $Al_2O_3 – 3*K_2O$ **(A)**
(if projected from K-feldspar) $Al_2O_3 – K_2O$
FeO (+ MnO) **(F)**
Mg **(Mg)**

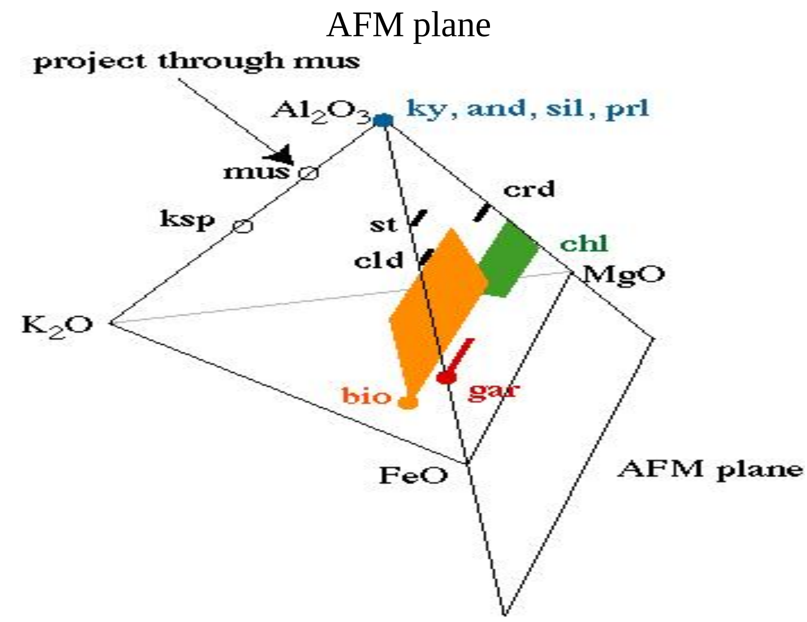
The A(K)FM diagram is used to describe the phase relations of pelites

1. To start, we assume excess SiO_2, H_2O, meaning that quartz/coesite and H_2O are stable in all mineral assemblages.
2. Then we assume that plagioclase is also stable and of an unknown, but unimportant, composition; by this we ignore the effects of Na and Ca.
3. This results in a tetrahedron of $A=Al_2O_3$, $K=K_2O$, $F=FeO$, $M=MgO$:



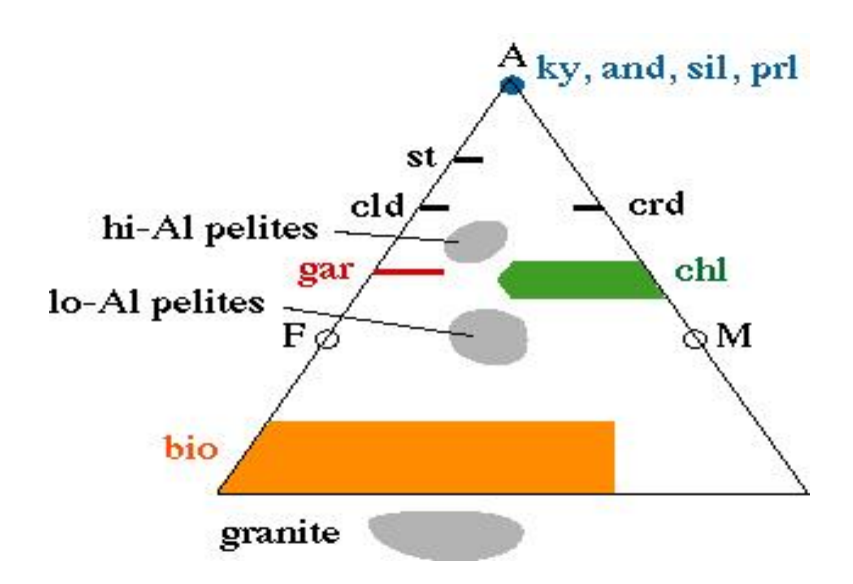
4. To render this diagram in easier-to-understand-and-draw 2D, we project the compositions in the tetrahedron from muscovite $KAl_3Si_3O_{10}(OH)_2$ onto the

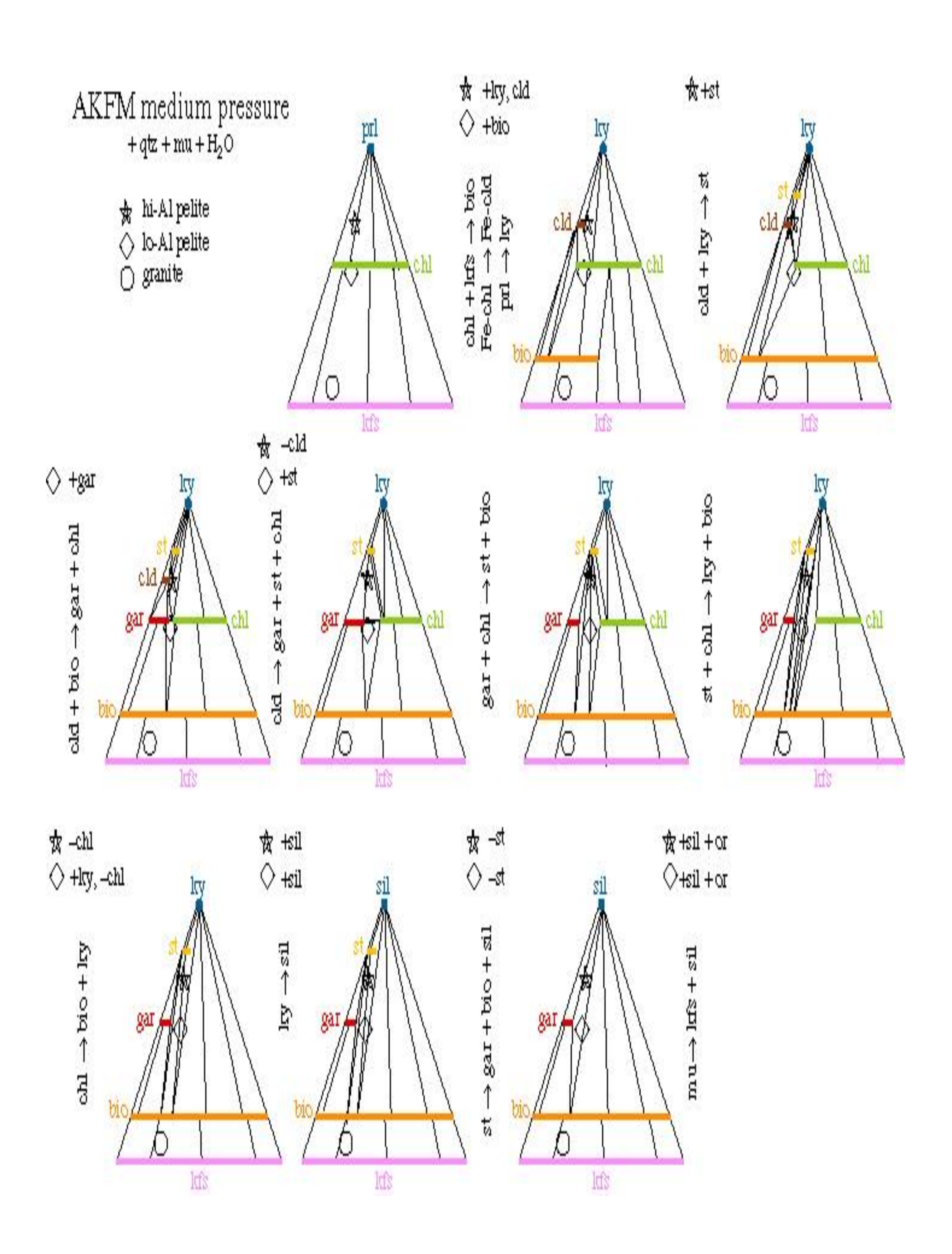
AFM plane

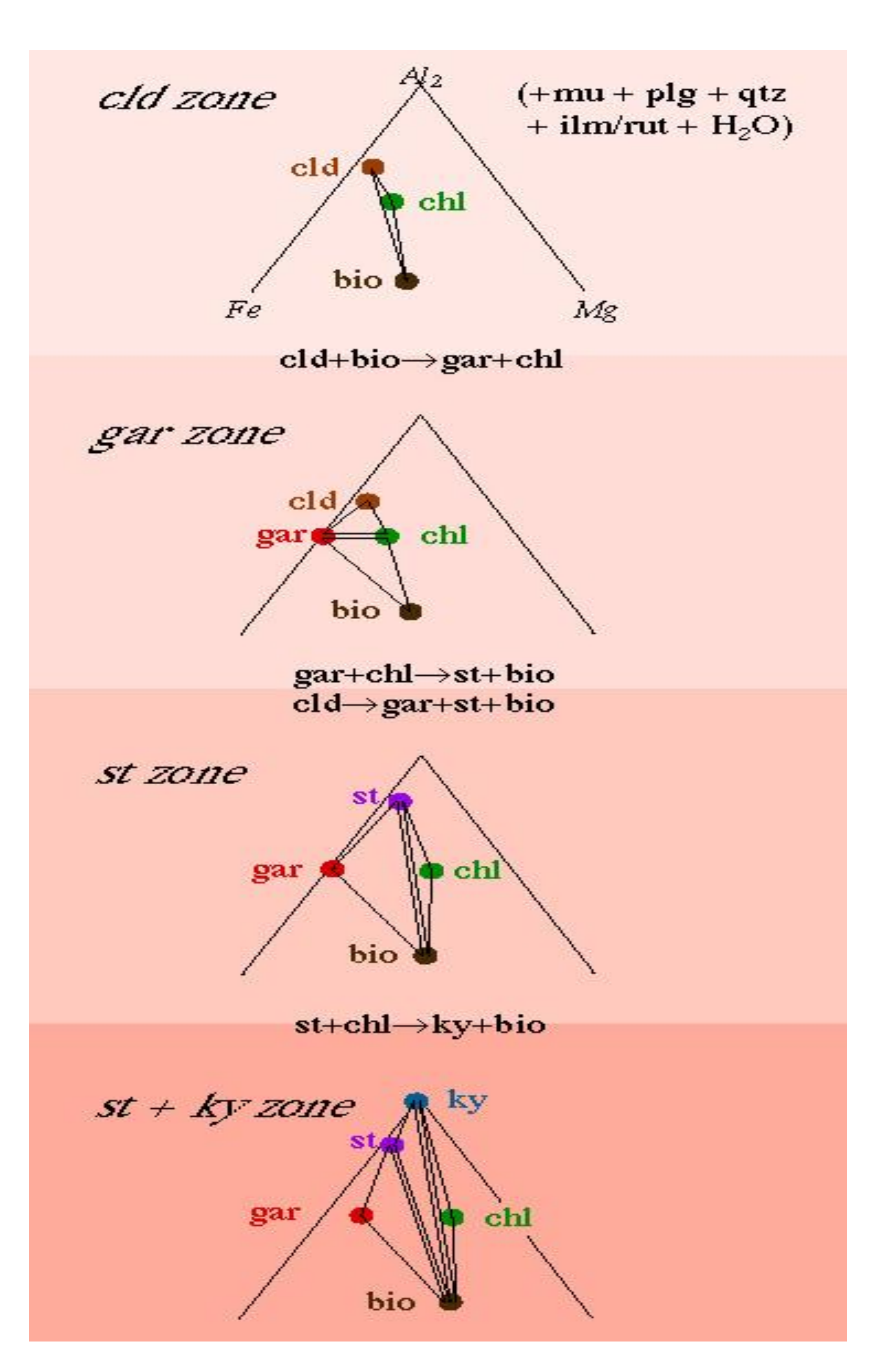


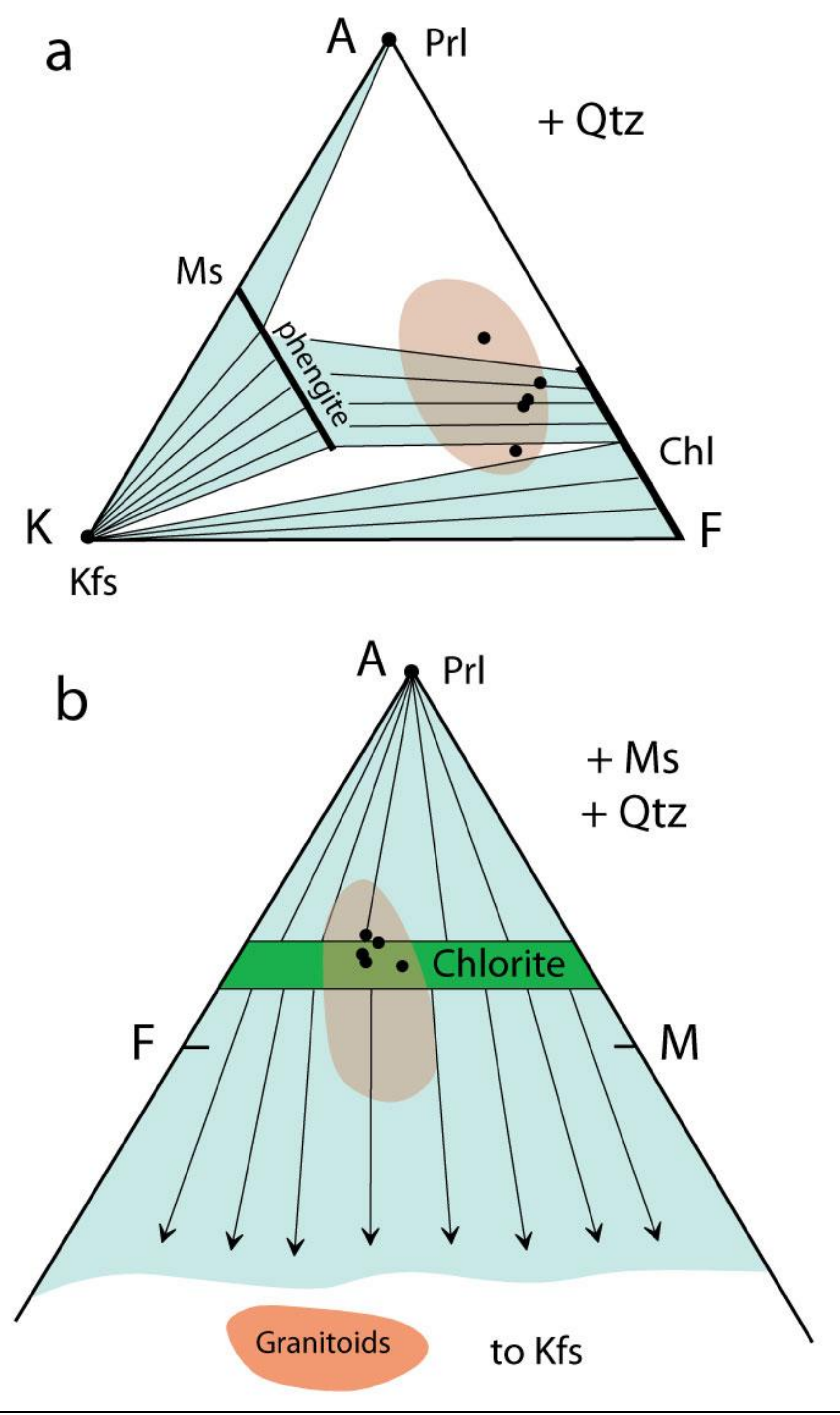
5. This results in a common pelitic assemblage such as st + gar + bio + mus + plg + qtz + H_2O (7 phases) plotting as a triangle. This is convenient, and possible only because we have assumed that i) qtz + H_2O are in excess, ii) plagioclase is present, and iii) muscovite of fixed composition is present.

6-

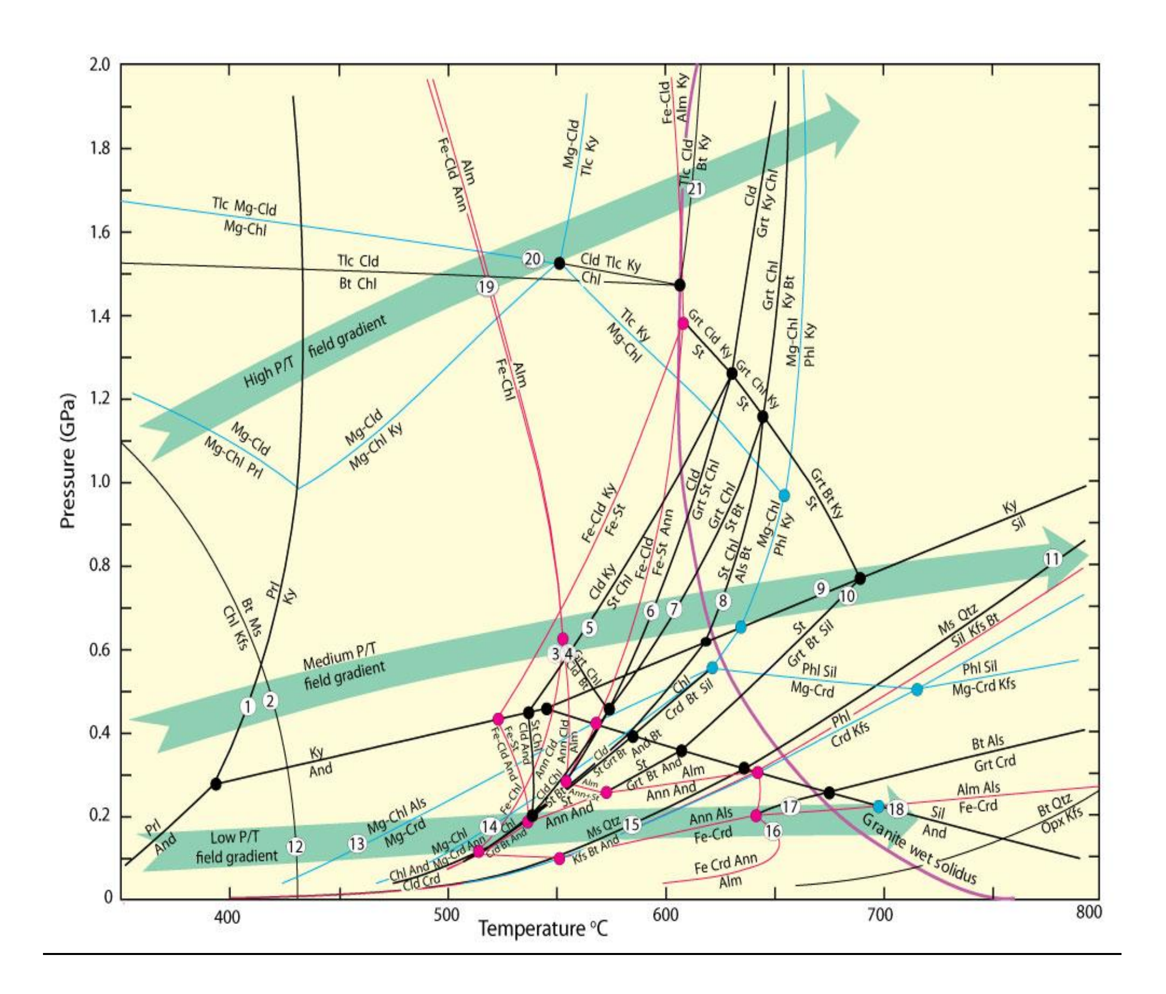


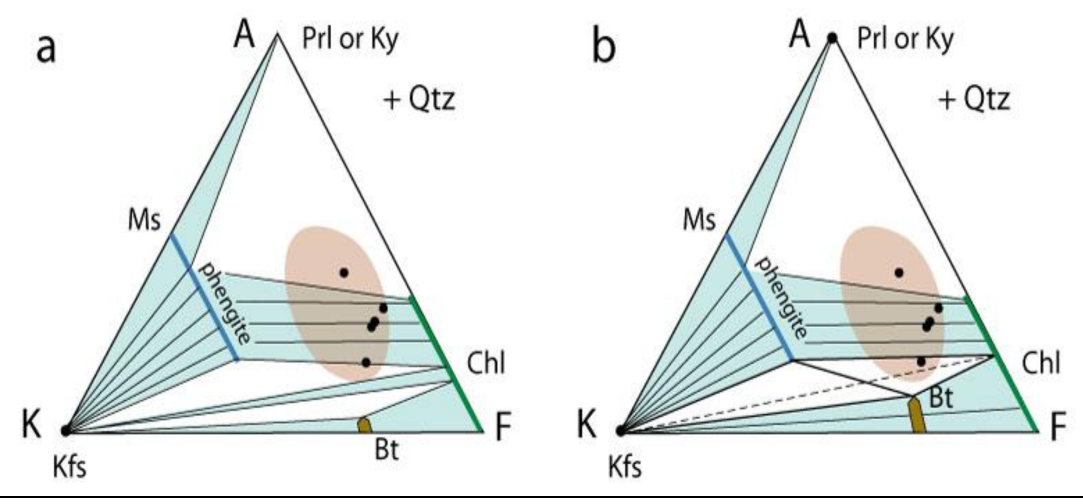

AKFM medium pressure
+qtz+mu+H_2O
hi-Al pelite
lo-Al pelite
granite
prl
chl
lcfs
+ky, cld
+bio
chl + kfs → bio
Fe-chl → Fe-cld
prl → ky
ky
cld
bio
+st
cld + ky → st
st
+gar
cld + bio → gar + chl
gar
-cld
+st
cld → gar + st + chl
gar + chl → st + bio
st + chl → ky + bio
-chl
+ky, -chl
chl → bio + ky
+sil
+sil
ky → sil
sil
-st
-st
st → gar + bio + sil
+sil +or
+sil +or
mu → kfs + sil


cld zone
Al_2
(+mu + plg + qtz
+ ilm/rut + H_2O)
cld
chl
bio
Fe
Mg
cld+bio⟶gar+chl
gar zone
cld
gar
chl
bio
gar+chl⟶st+bio
cld⟶gar+st+bio
st zone
st
gar
chl
bio
st+chl⟶ky+bio
st + ky zone
ky
st
gar
chl
bio

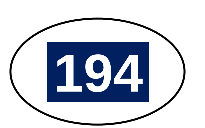


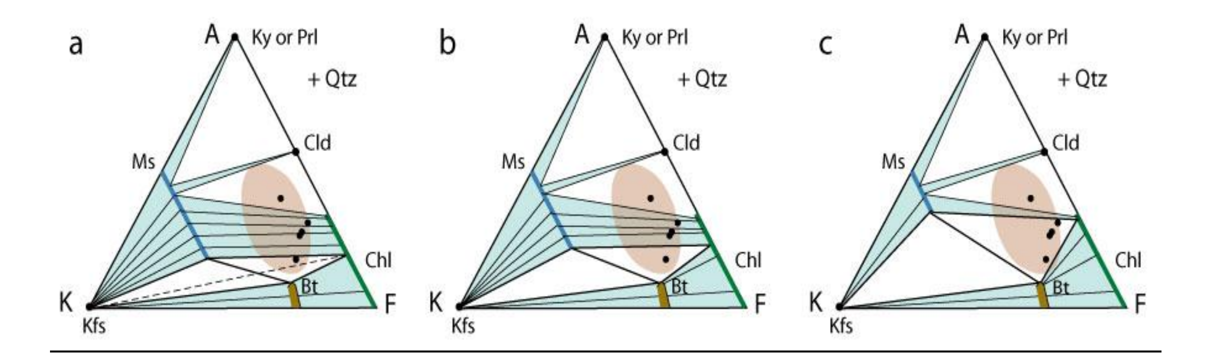
projected from Ms compatibility diagrams for pelitic rocks in the chlorite zone of the lower greenschist facies. Shaded areas represent the common range of pelite and granitoid rock compositions. Small black dots are the analyses from Table 28.1.



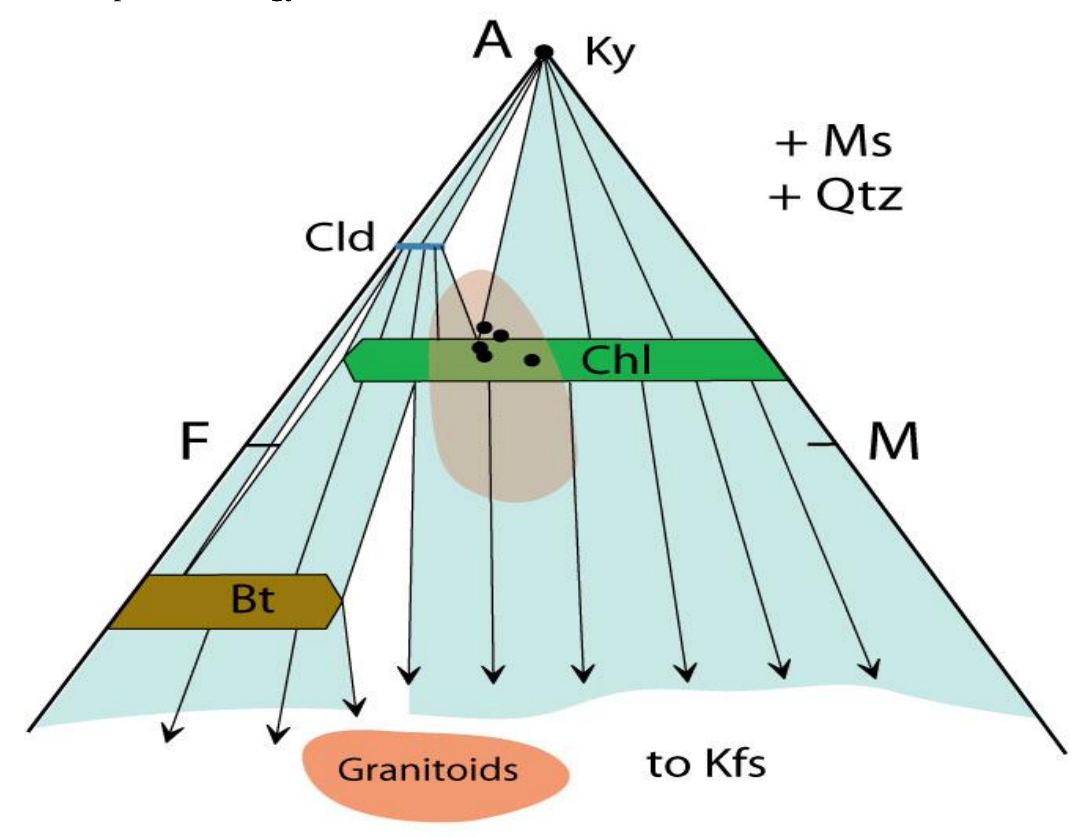


Greenschist facies AKF compatibility diagrams (using the Spear, 1993, formulation) showing the biotite-in isograd reaction as a “tie-line flip.” In (a), below the isograd, the tie-lines connecting chlorite and K-Feldspar shows that the mineral pair is stable. As grade increases the Chl-Kfs field shrinks to a single tie-line. In (b), above the isograd, biotite + phengite is now stable, and chlorite + K-feldspar are separated by the new biotite-phengite tie-line, so they are no longer stable together. Only the most Al-poor portion of the shaded natural pelite range is affected by this reaction.

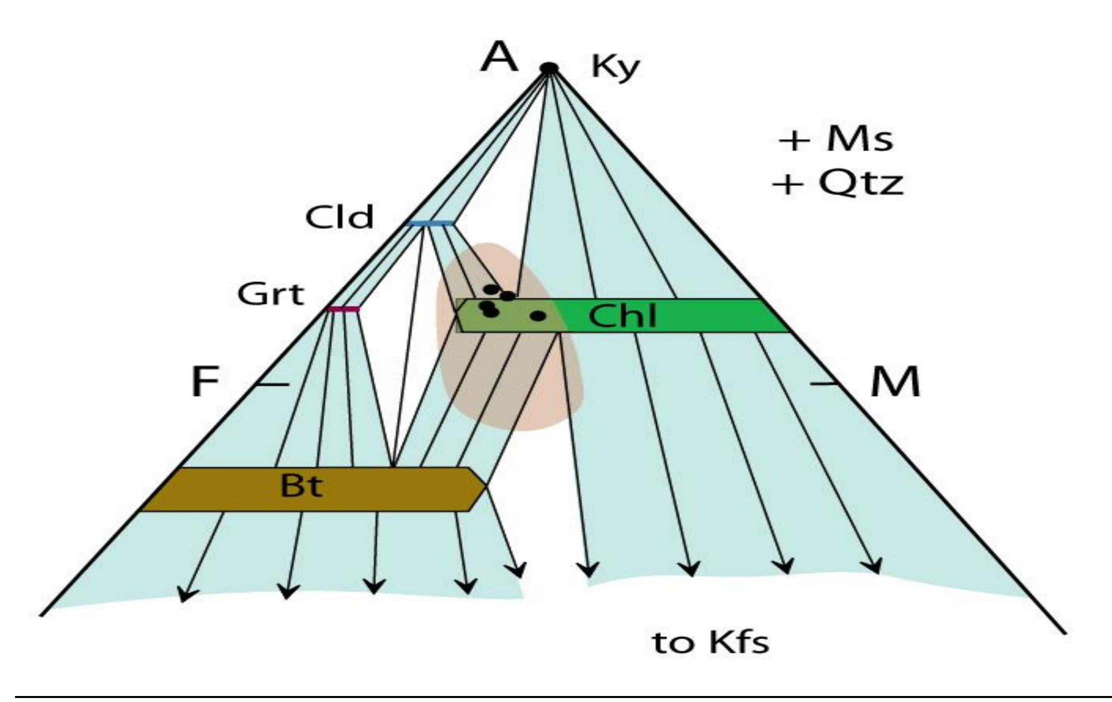




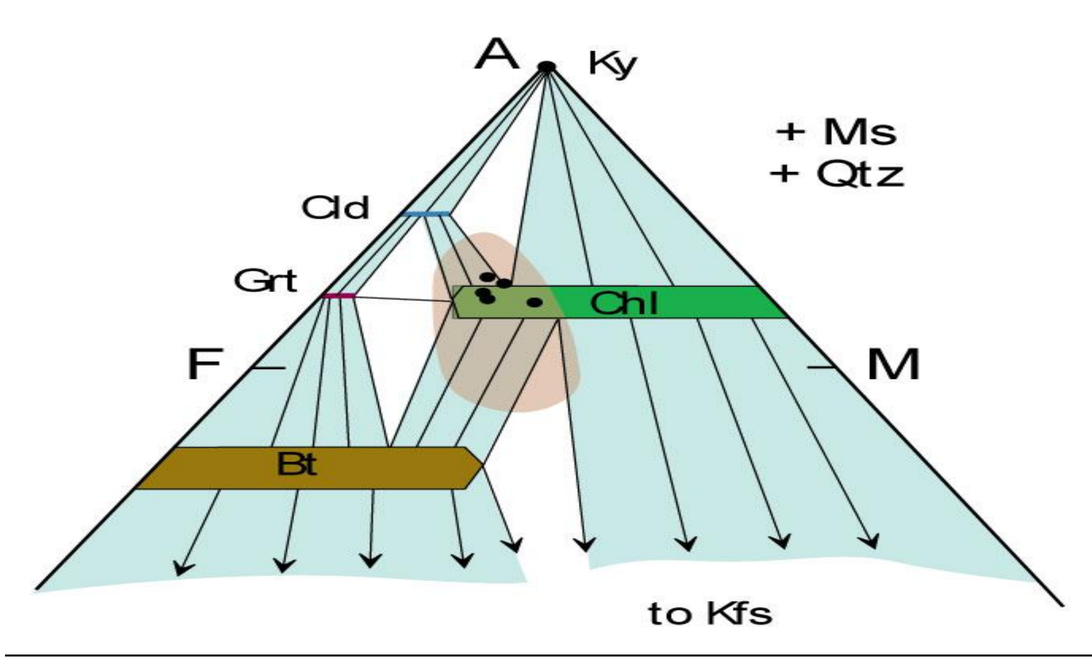
A series of AKF compatibility diagrams (using the Spear, 1993, formulation) illustrating the migration of the Ms-Bt-Chl and Ms-Kfs-Chl sub-triangles to more Al-rich compositions via continuous reactions in the biotite zone of the greenschist facies above the biotite isograd. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



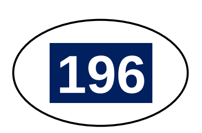
AFM compatibility diagram (projected from Ms) for the biotite zone, greenschist facies, above the chloritoid isograd. The compositional ranges of common pelites and granitoids are shaded. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

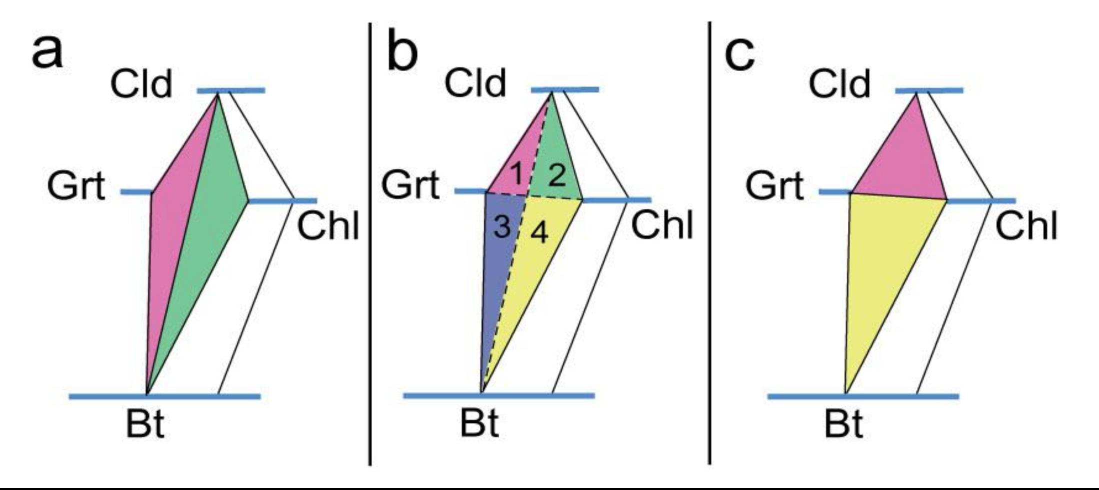


AFM compatibility diagram (projected from Ms) for the upper biotite zone, greenschist facies. Although garnet is stable, it is limited to unusually Fe-rich compositions, and does not occur in natural pelites (shaded). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

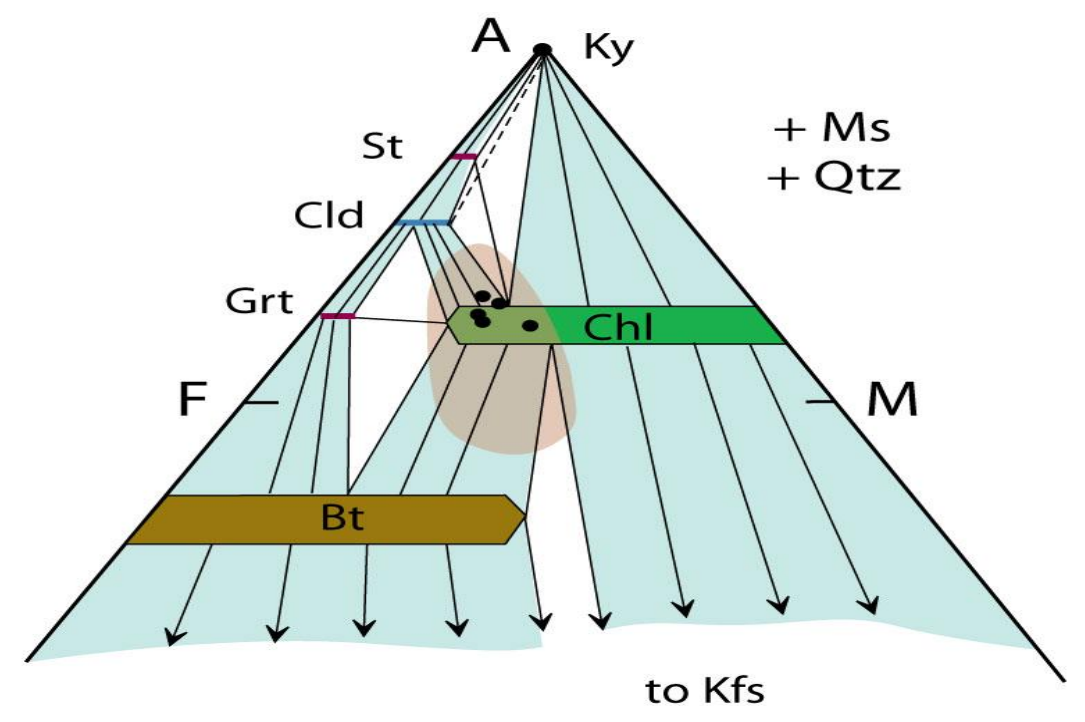


AFM compatibility diagram (projected from Ms) for the garnet zone, transitional to the amphibolite facies, showing the tie-line flip associated with reaction (28.8) (compare to Figure 28.6) which introduces garnet into the more Fe-rich types of common (shaded) pelites. After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

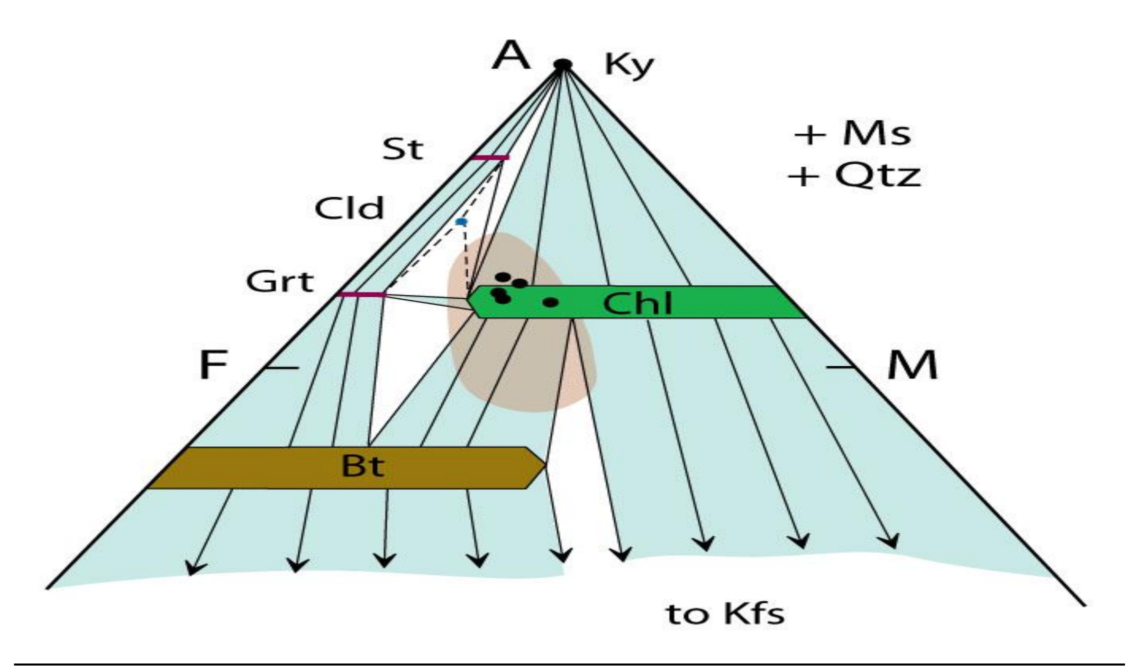




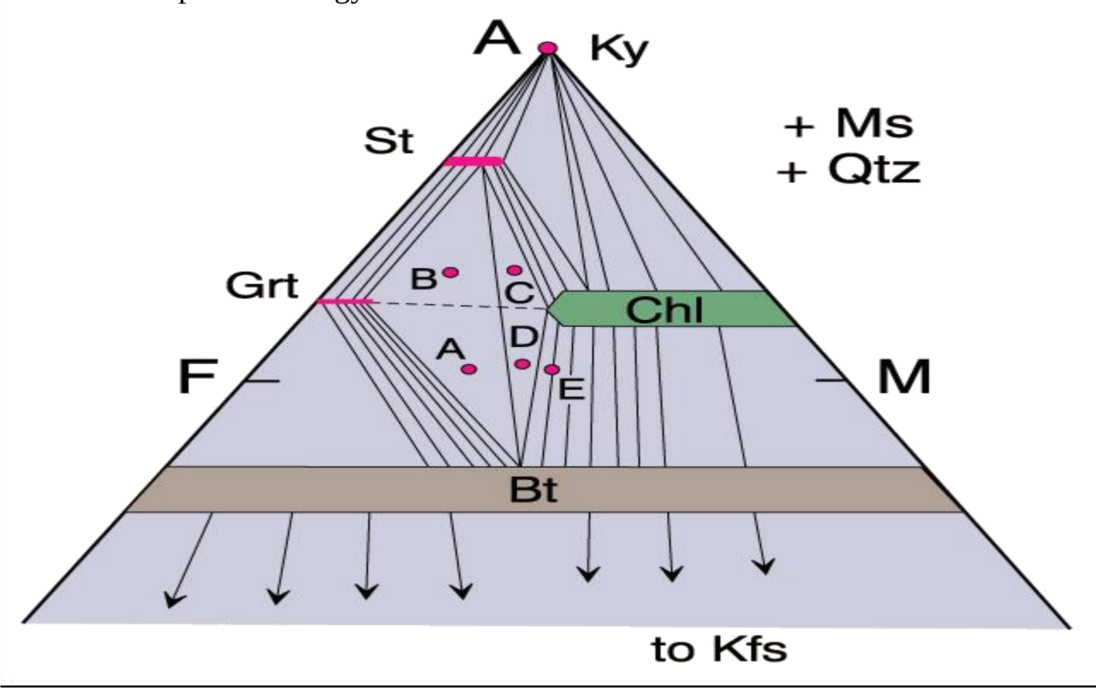
An expanded sketch of the Grt-Cld-Chl-Bt quadrilateral from Figures 28.6 and 28.7 illustrating the tie-line flip of reaction (28.7). a. Before flip. b. During flip (at the isograd). c. After flip (above the isograd). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



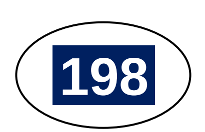
AFM compatibility diagram (projected from Ms) in the lower staurolite zone of the amphibolite facies, showing the change in topology associated with reaction (28.9) in which the lower-grade Cld-Ky tie-line (dashed) is lost and replaced by the St-Chl tie-line. This reaction introduced staurolite to only a small range of Al-rich metapelites. After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

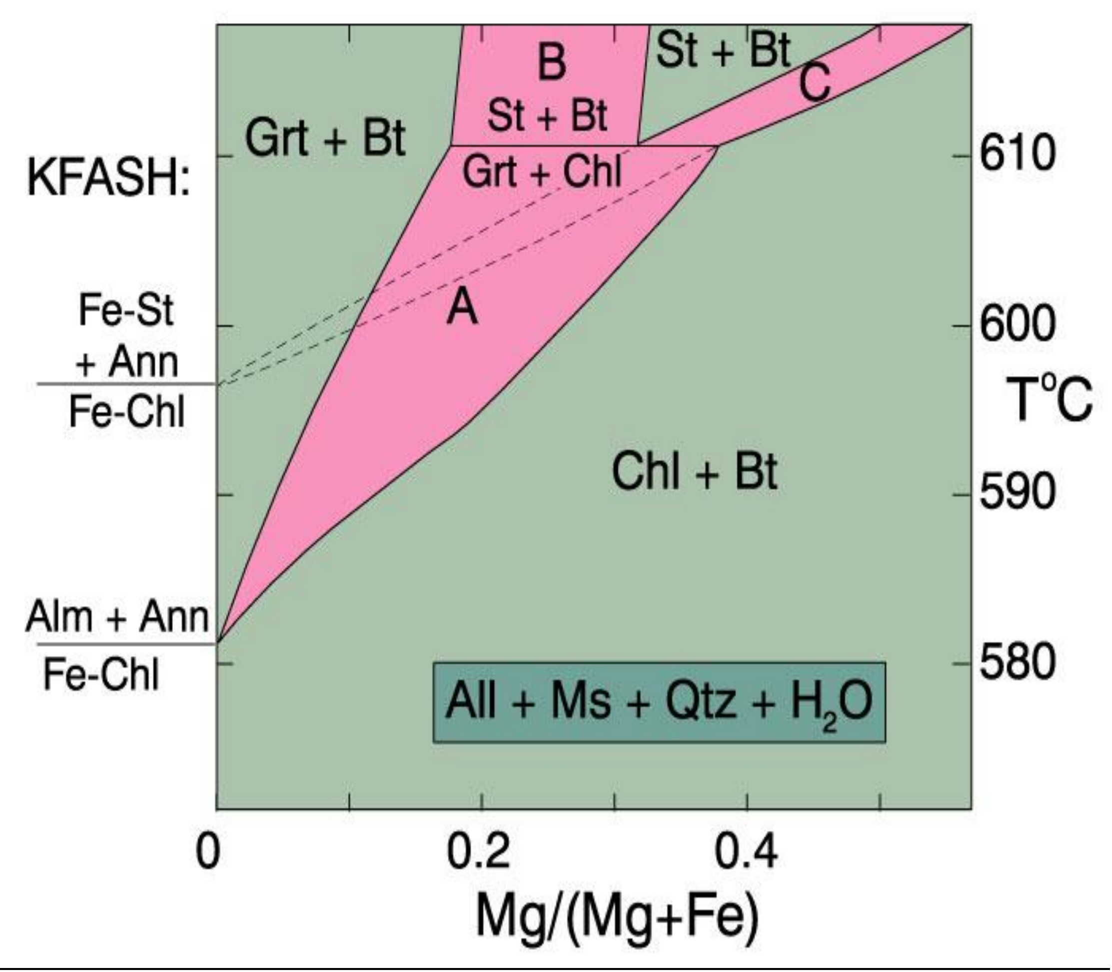


AFM compatibility diagram (projected from Ms) in the staurolite zone of the amphibolite facies, showing the change in topology associated with the terminal reaction (28.11) in which chloritoid is lost (lost tie-lines are dashed), yielding to the Grt-St-Chl sub-triangle that surrounds it. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

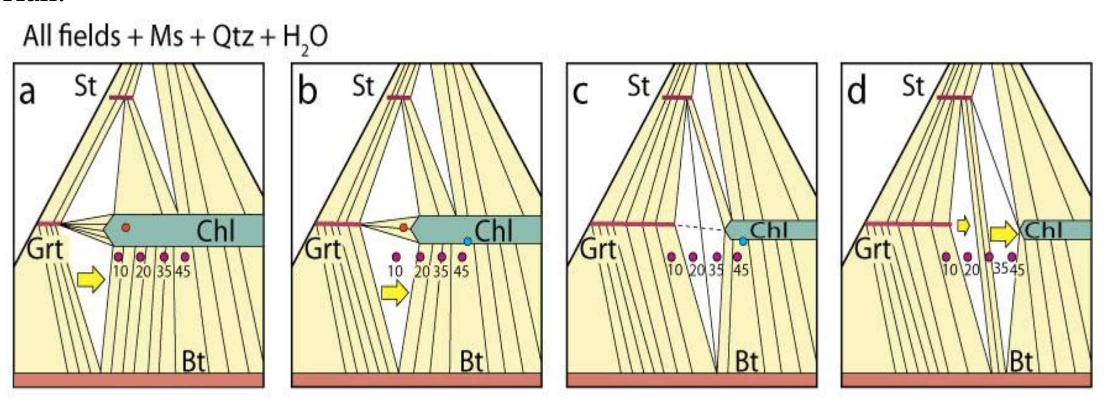


. AFM compatibility diagram (projected from Ms) for the staurolite zone, amphibolite facies, showing the tie-line flip associated with reaction (28.12) which introduces staurolite into many low-Al common pelites (shaded). After Carmichael (1970) *J. Petrol.*, 11, 147-181. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

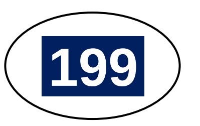




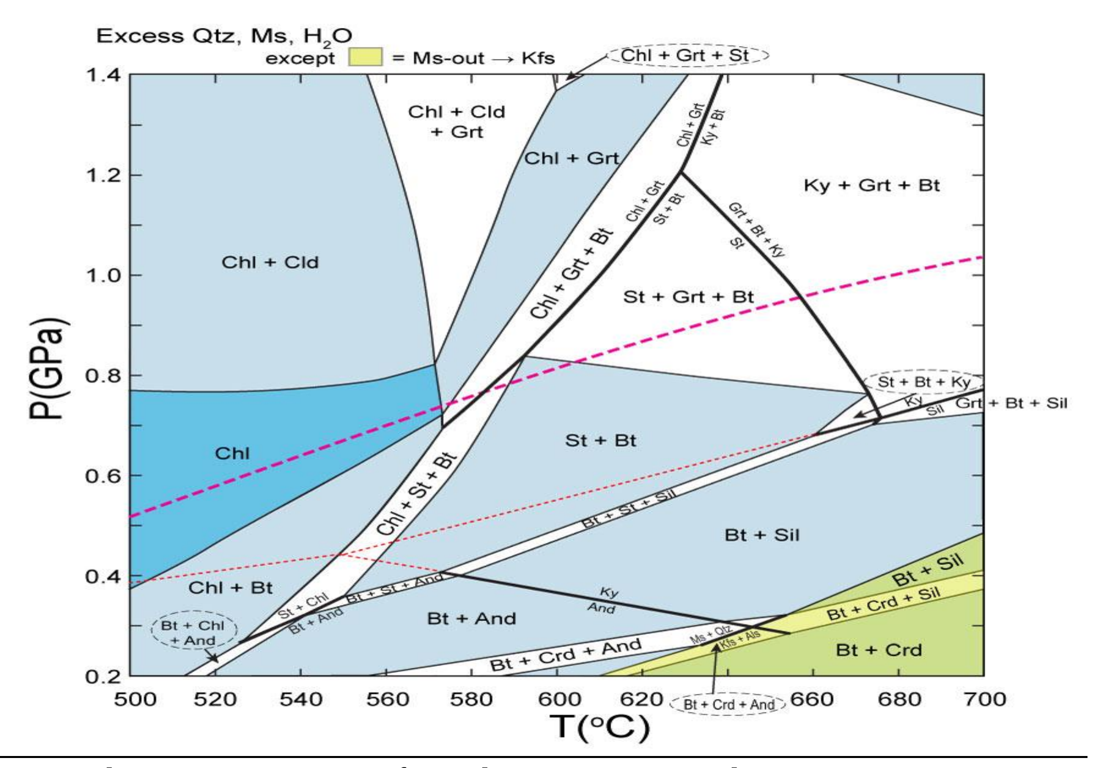
T-X_{Mg} "pseudosection" diagram in the system KFMASH of variable Mg/Fe for a "common pelite" with molar A:F:K = 0.92:1:0.28, calculated by Powell *et al*. (1998) *J. Metam. Geol.*, 16, 577-588. I have modified the temperatures of the original isobaric diagram to conform with the specified medium P/T trajectory in Figure 28.2. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



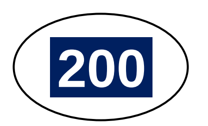
A schematic expanded view of the Grt-St-Chl-Bt quadrilateral from Figure 28.11 illustrating the progressive metamorphism of compositions with 100*Mg/(Mg + Fe), or Mg#, of 10, 20, 35, and 45 from Figure 28.12. (a) At a grade below 585°C at which all four compositions contain chlorite + biotite (+ Ms + Qtz). (b) As reaction (28–12) proceeds, the most Fe-rich chlorite breaks down and the Chl-Grt-Bt triangle shifts to the right (arrow). (c) Further shift of the Chl-Grt-Bt triangle due to reaction (28.12) encompasses Mg#20 and 35 and leaves Mg#10. The Grt-Chl field shrinks to a single

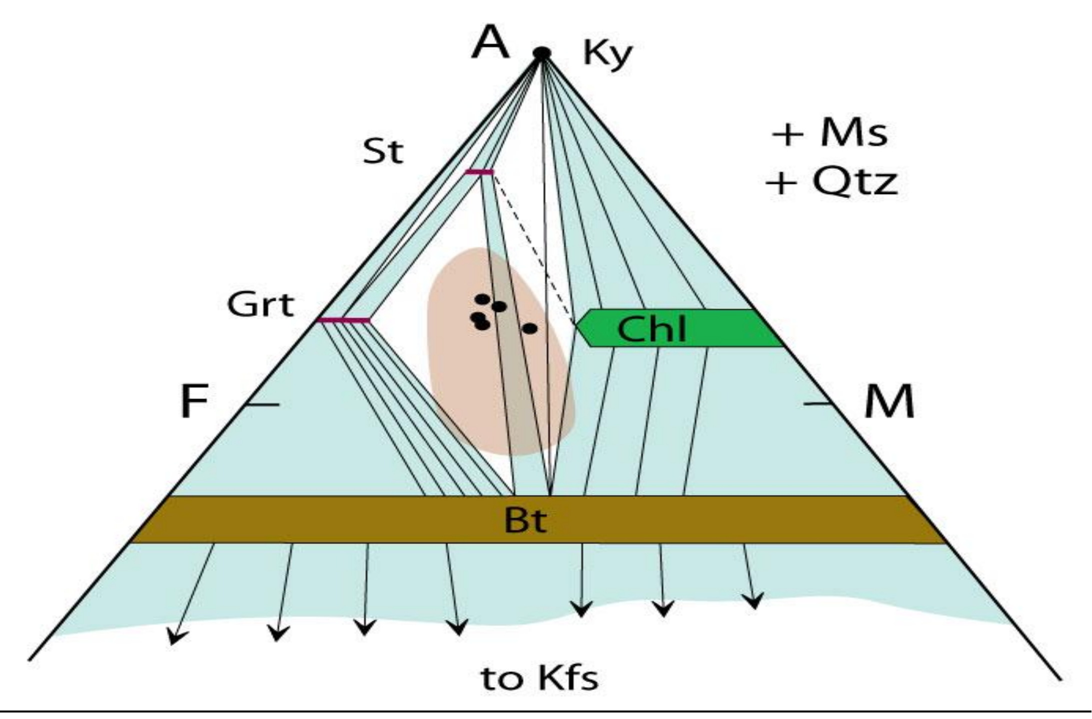


tie-line, then disappears as Reaction (28.12) causes a tie-line flip to St-Bt. Composition Mg#20 thereby loses Chl and gains St as composition Mg#35 loses Grt and gains St. (d) Migration of the new Chl-St-Bt triangle (arrow) due to Reaction (28.14) encompasses Mg#45 (which develops St) and leaves Mg#35 (which loses Chl). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

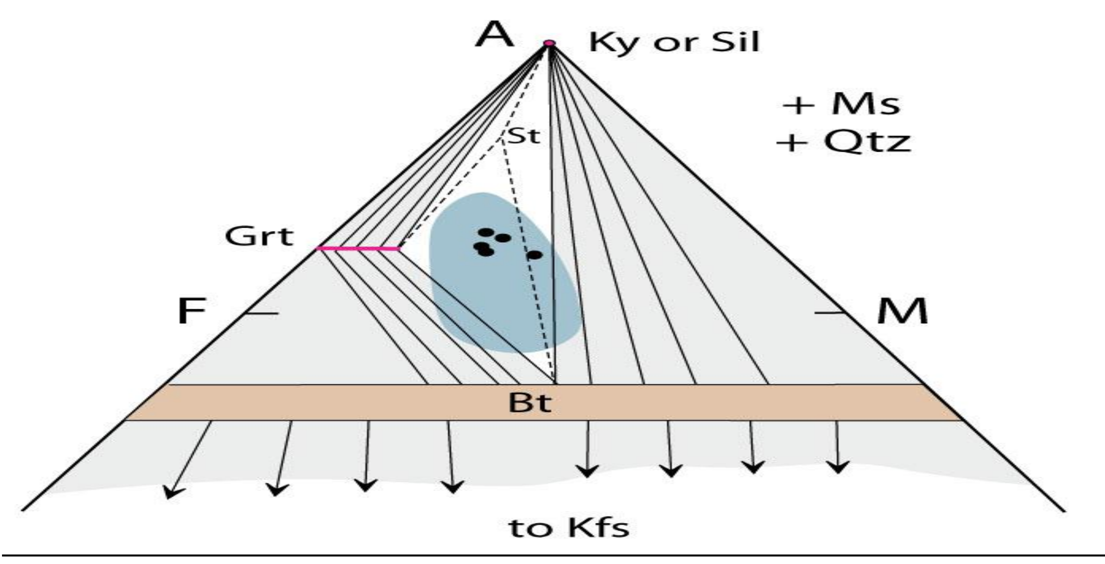


P-T pseudosection in *KFMASH* for mol% SiO_2 = 76.14, Al_2O_3 = 11.25, MgO = 4.89, FeO = 7.33, K_2O = 3.39. This composition has Qtz and Ms in excess and H_2O was set to saturated. Calculated using both THERMOCALC and PERPLEX and the November 2003 Holland-Powell internally-consistent thermodynamic database with quite similar results. Based on Powell et al. (1998). Extensions of Al_2SiO_5 polymorph reactions shown as dashed curves for clarity. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

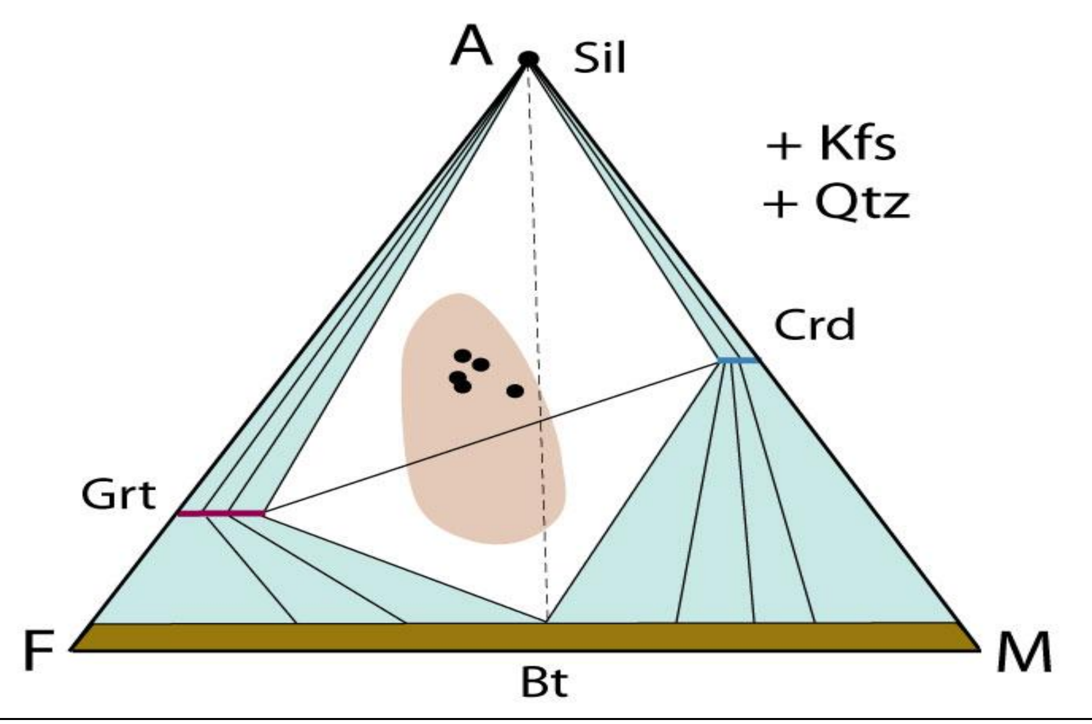




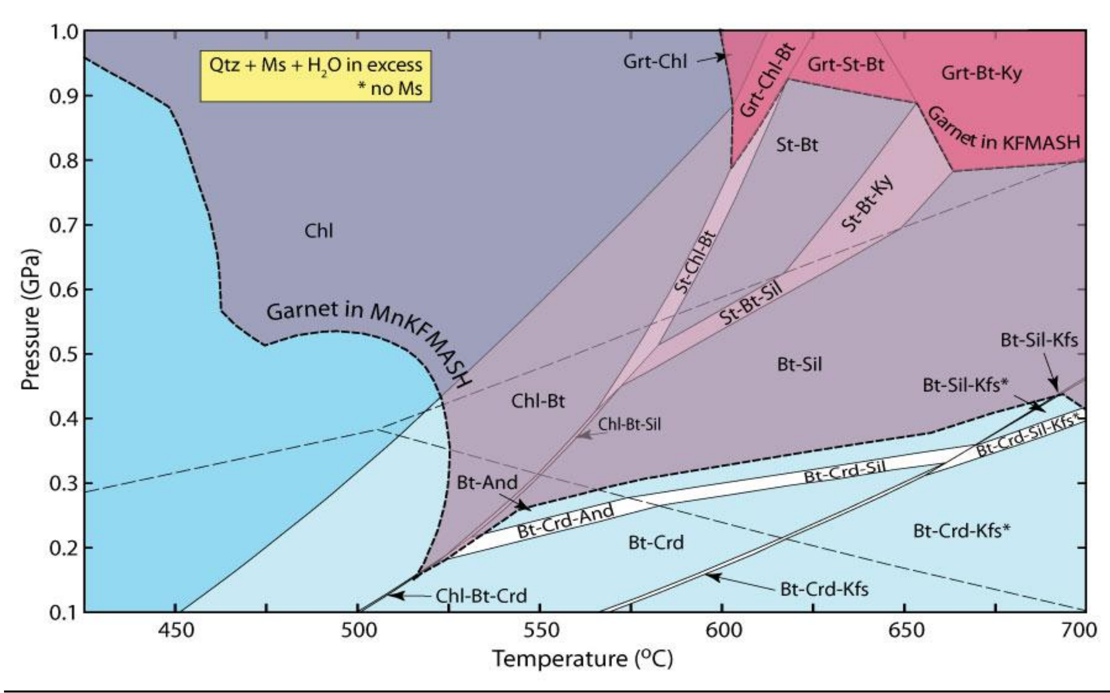
AFM compatibility diagram (projected from Ms) for the kyanite zone, amphibolite facies, showing the tie-line flip associated with reaction (28.15) which introduces kyanite into many low-Al common pelites (shaded). After Carmichael (1970) *J. Petrol.*, 11, 147-181. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Ha



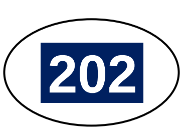
AFM compatibility diagram (projected from Ms) above the sillimanite and "staurolite-out" isograds, sillimanite zone, upper amphibolite facies. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



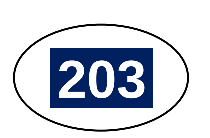
AFM compatibility diagram (projected from K-feldspar) above the cordierite-in isograds, granulite facies. Cordierite forms first by reaction (29-14), and then the dashed Sil-Bt tie-line is lost and the Grt-Crd tie-line forms as a result of reaction (28.17). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

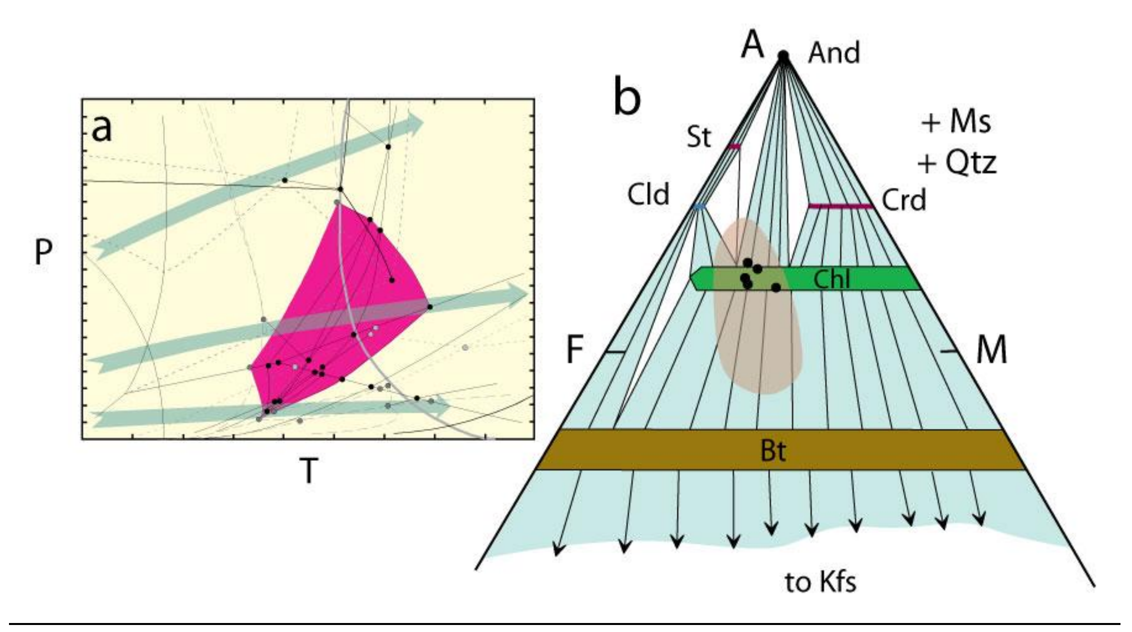


P-T pseudosection in *KFMASH* for X_{bulk}: Al_2O_3 = 45.80, FeO = 21.93, MgO = 19.59, K_2O = 9.01 (in mol%) calculated using the program THERMOCALC by Tinkham et al. (2001). The cross-hatched area in the upper right is the stability range of garnet in *KFMASH*. The dashed curve is the stability limit of garnet in *MnKFMASH* (after Tinkham et al., 2001). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

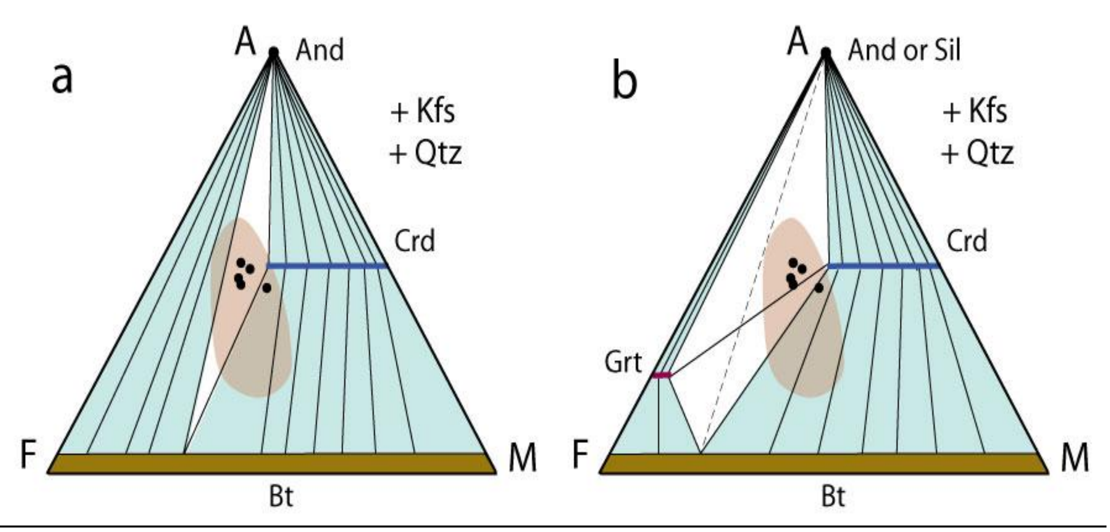


Schematic *AFM* compatibility diagrams (projected from Ms) for low P/T metamorphism of pelites. (a) Cordierite forms between andalusite and chlorite along the Mg-rich side of the diagram via reaction (28.24b) in the albite-epidote hornfels facies. Chloritoid has formed earlier (via Reaction 28.4) and the Chl-Cld-Bt sub-triangle migrates toward the right (block arrow) while the Chl-Cld-And sub-triangle migrates toward the left. (b) Chl migrates off the A-M edge to form a Chl + Bt + Crd sub-triangle via the continuous version of the same Reaction (28.24b) in *KFMASH*. The compositional range of chloritoid and chlorite are reduced and that of cordierite expands as the Chl-Cld-And, And-Chl-Crd and Chl-Crd-Bt sub-triangles all migrate toward more Fe-rich compositions. The Chl + Ctd area shrinks to a single-tie-line (dashed) which then "flips" to the crossing And + Bt tie-line. Andalusite and cordierite may be introduced into the shaded region of pelite compositions by these combined processes. (c) Migration of the Chl-And-Bt sub-triangle to the left (arrow) results from the discontinuous reaction Chl (+Ms + Qtz) → And + Bt in the lower to mid hornblende hornfels facies. (d) Chlorite is lost in Ms-bearing pelites as a result of reaction (28–25). Partially created using the program Gibbs (Spear, 1999).





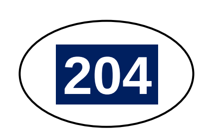
The stability range of staurolite on Figure 28.2 (red). b. AFM compatibility diagram (projected from Ms) in the hornblende hornfels facies in the vicinity of 530-560°C at pressures greater than 0.2 GPa, in which staurolite is stable and may occur in some high-Fe-Al pelites (shaded). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



AFM compatibility diagrams (projected from Kfs) in the lowermost pyroxene hornfels facies.

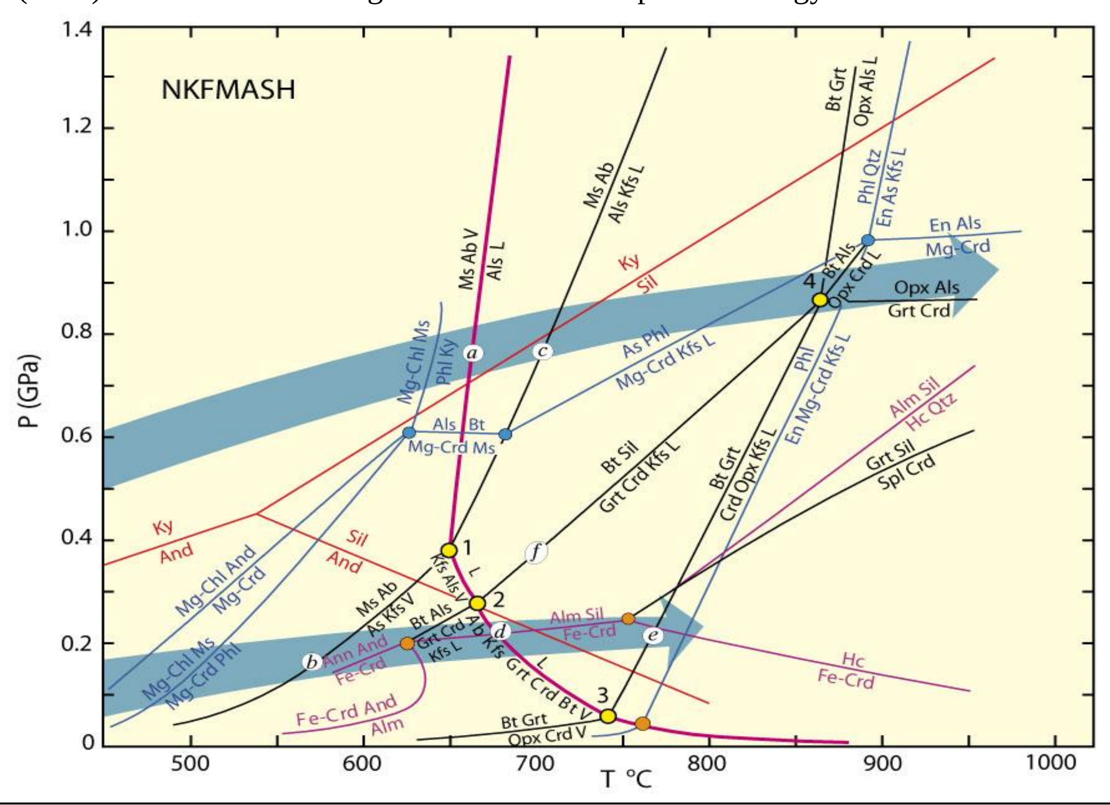
a. The compositional range of cordierite is reduced as the Crd-And-Bt sub-triangle migrates toward more Mg-rich compositions. Andalusite may be introduced into Al-rich pelites

b. Garnet is introduced to many Al-rich pelites via reaction (28.27). Winter (2010) An Introduction to Igneous and Metamorphic.

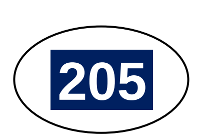




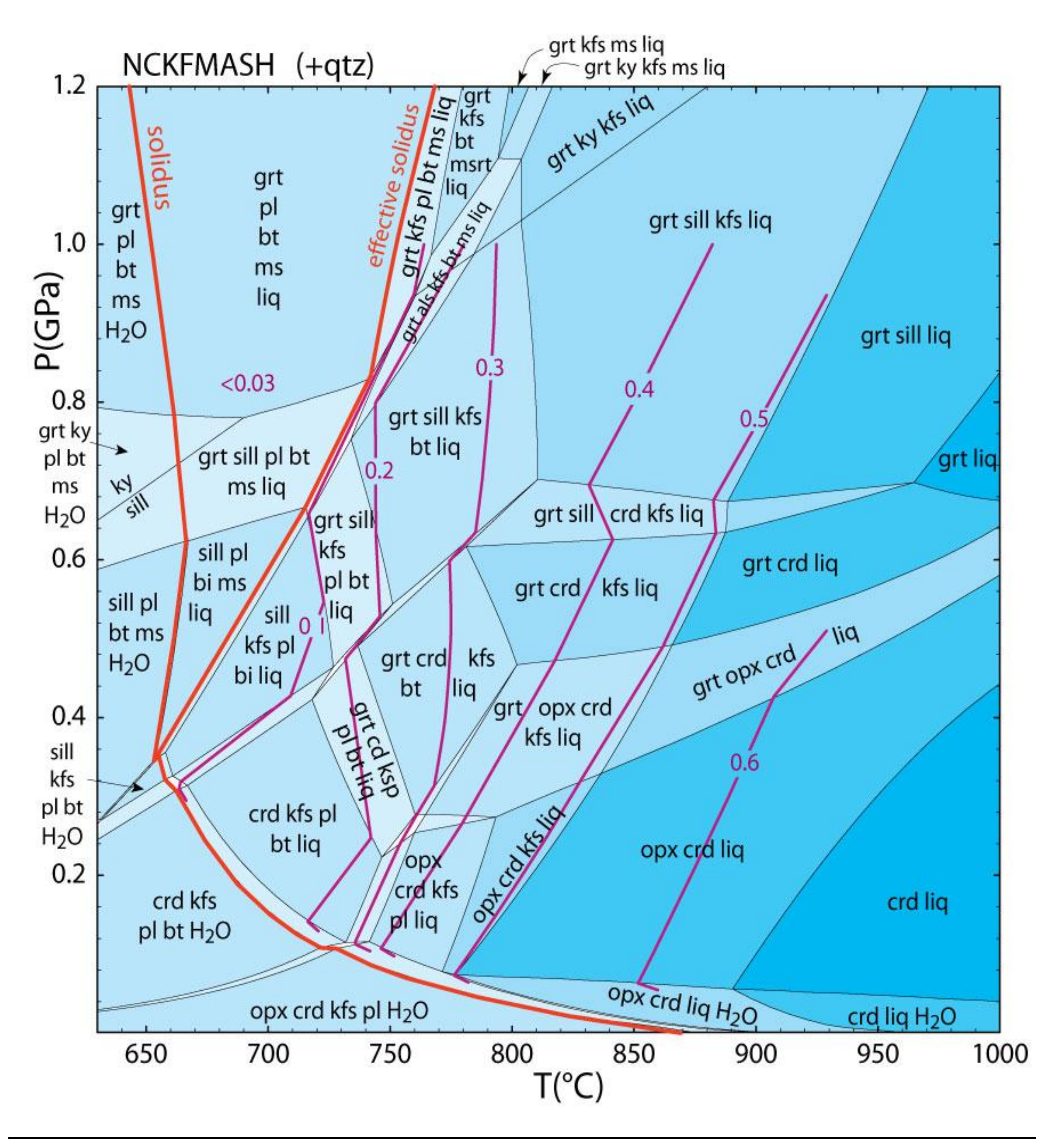
Veins developed in pelitic hornfelses within a few meters of the contact with diorite. The vein composition contrasts with that of the diorite, and suggests that the veins result from localized partial melting of the hornfelses. Onawa aureole, Maine. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



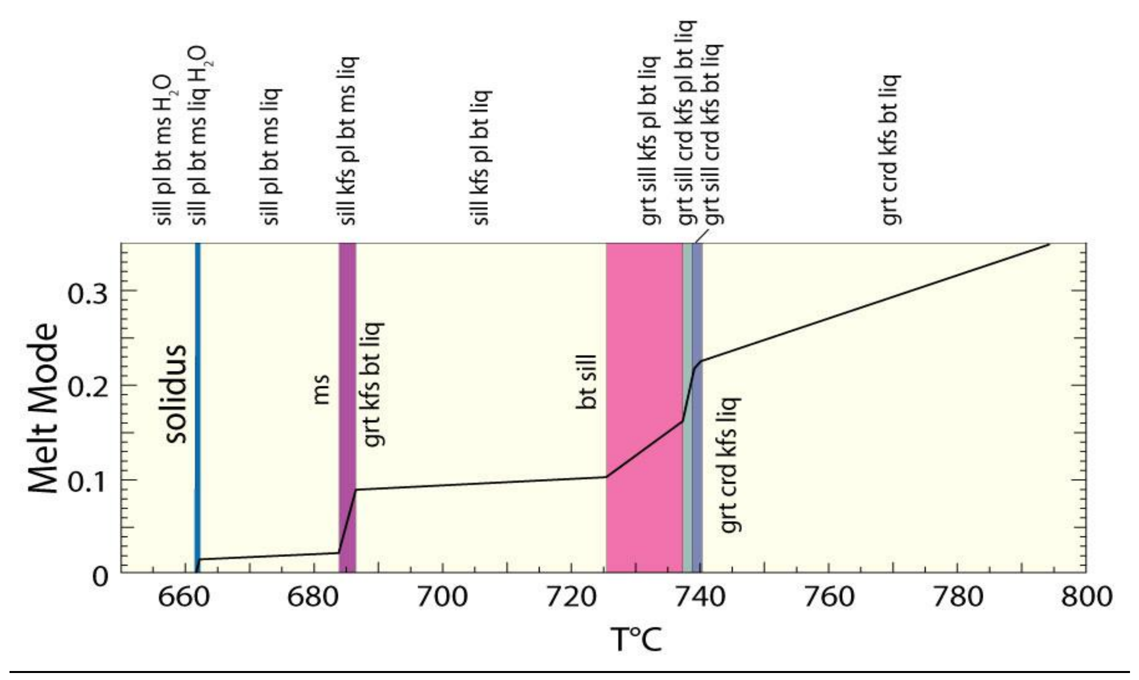
Simplified high-temperature petrogenetic grid showing the location of selected melting and dehydration equilibria in the Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (NKFMASH) system, with sufficient sodium to stabilize albite. Also shown are some equilibria in the KFASH (orange) and KMASH (blue) systems. The medium and low P/T metamorphic field gradients from Figure 28.2 (broad arrows) are included. The Al_2SiO_5 triple point is shifted as shown to 550°C and 0.45 GPa following the



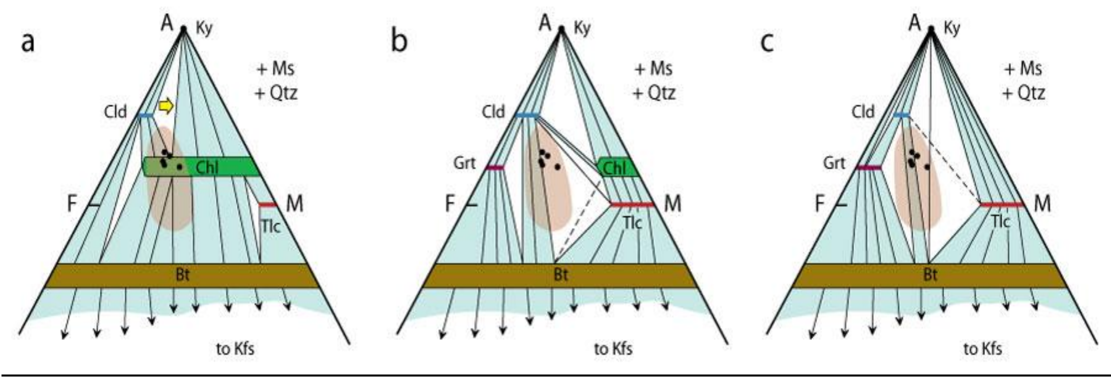
arguments of Pattison (1992), allowing for the coexistence of andalusite and liquid. V = H_2O-rich vapor, when present in fluid-saturated rocks. After Spear *et al*. (1999).



P-T pseudosection for the average pelite composition of Powell et al. (1998) with "representative" Na_2O and Cao added and just sufficient H_2O to saturate immediately subsolidus at 0.6 GPa. Mol.% Al_2O_3 = 30.66, FeO = 23.74, MgO = 12.47, CaO = 0.97, Na_2O = 1.94, K_2O = 9.83, H_2O = 20.39 (and quartz in excess). Solidus and melt mode (volume fraction of melt produced) overlain as contours. "Effective solidus" is when the melt fraction exceeds a few hundredths of a percent. After White et al. (2001).



Melt mode produced (molar on a one-oxygen basis) upon heating at 0.5 GPa of the same X_{bulk} as in Figure 28.24. After White et al. (2001).



AFM compatibility diagrams (projected from muscovite) for the eclogite facies of high P/T metamorphism of pelites. a. Talc forms between biotite and chlorite along the Mg-rich side of the diagram via reaction (28.35). b. At a higher grade the Chl-Bt tie-line flips to the Tlc-Cld tie-line via reaction (28.36). c. After chlorite breaks down the kyanite forms in many metapelites via reaction (28.36). After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



CHAPTER 10

Metamorphism of calcareous rocks

Metamorphism of carbonate rocks (Metcarbonate):

- **Metacarbonates** are metamorphosed calcareous (limestone and dolomite) rocks in which the carbonate component is predominant, with *granoblastic polygonal* texture .

Metacarbonates include:

i) Marbles are nearly pure carbonate (carbonate >50%).

ii) Calc-silicate rocks: carbonate is subordinate (carbonate <50%) and may be composed of Ca-Mg-Fe-Al silicate minerals, such as diopside, grossular, Ca-amphiboles, vesuvianite, epidote, wollastonite, plagioclase, talc, anthophyllite, etc.

iii) Skarn: calc-silicate rock formed by metasomatism between carbonates and silicate-rich rocks or fluids.

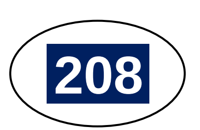
Carbonate rocks are predominantly carbonate minerals, usually limestone or dolostone. They may be pure carbonate, or they may contain variable amounts of other precipitates (such as chert or hematite) or detrital material (sand, clays, etc.).

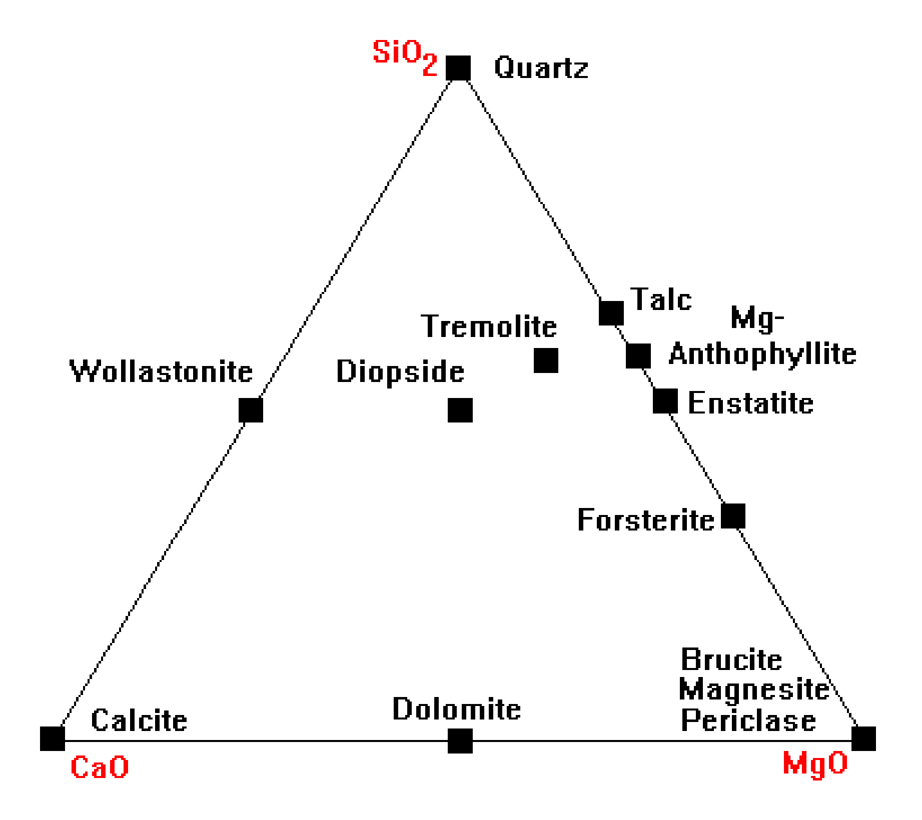
- **Chemically**, the carbonate rocks are rich in CaO, CO_2, MgO, and mad may SiO_2, Al_2O_3, FeO, and other subordinate oxides if the carbonate are impure.

Mineralogy of Metacarbonates:

Metacarbonate contain the following mineral assemblage:

- Carbonate minerals (Calcite and dolomite).
- Amphibole (anthophyllite Enstatite, Tremolite).
- Pyroxene (Diopside).
- Olivine.
- Talc.
- wollastonite .
- quartz.





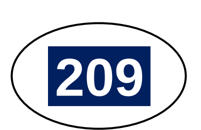
1- Pure Carbonates (Limestone and dolomite:

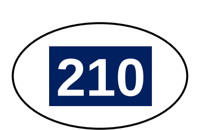
- Metamorphism of pure carbonate rocks yielded calcite and/or dolomite marbles. Many marbles are composed only of calcite and/or dolomite with minor quartz and phyllosilicates, originally of detrital origin.

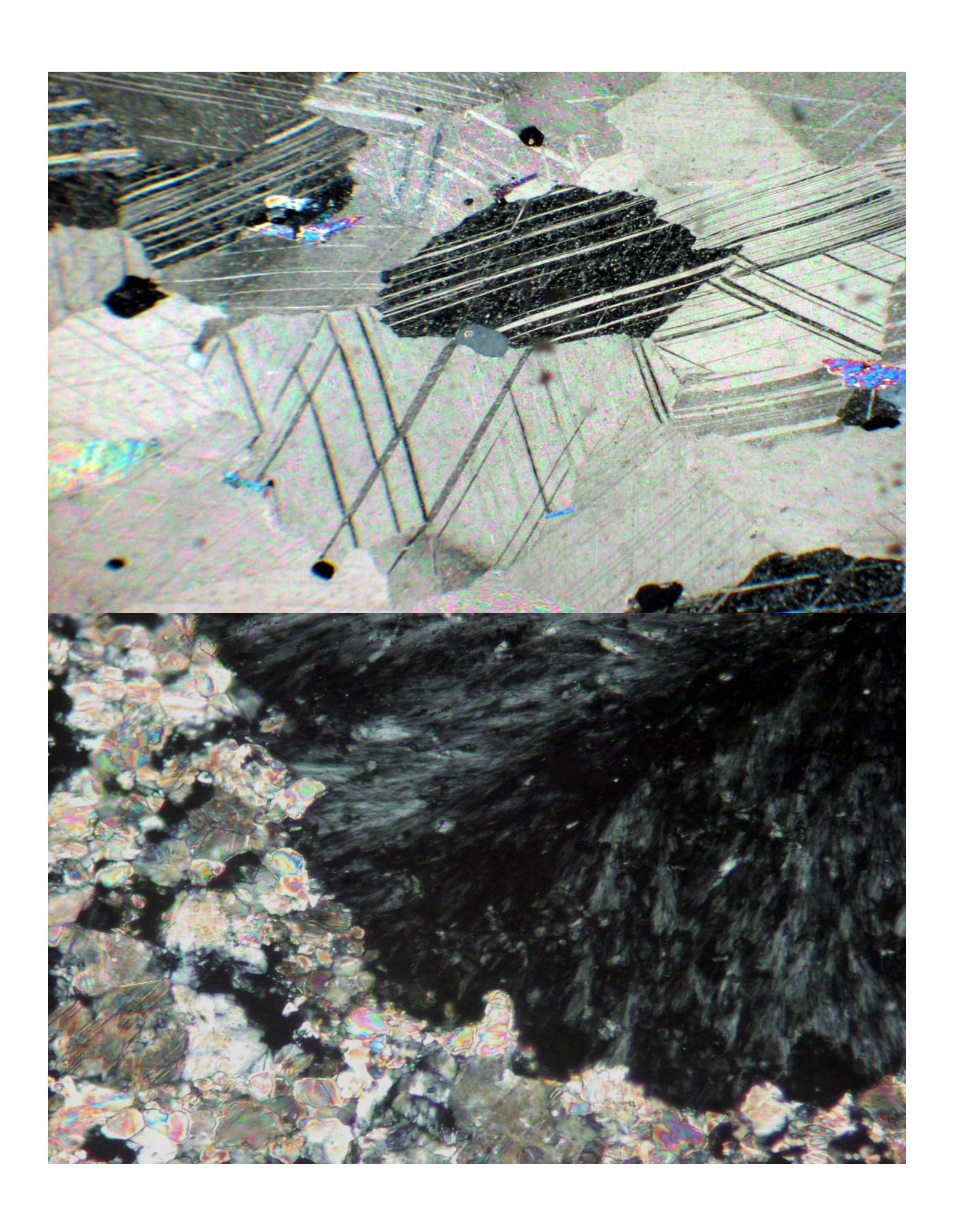
Calcite marble :

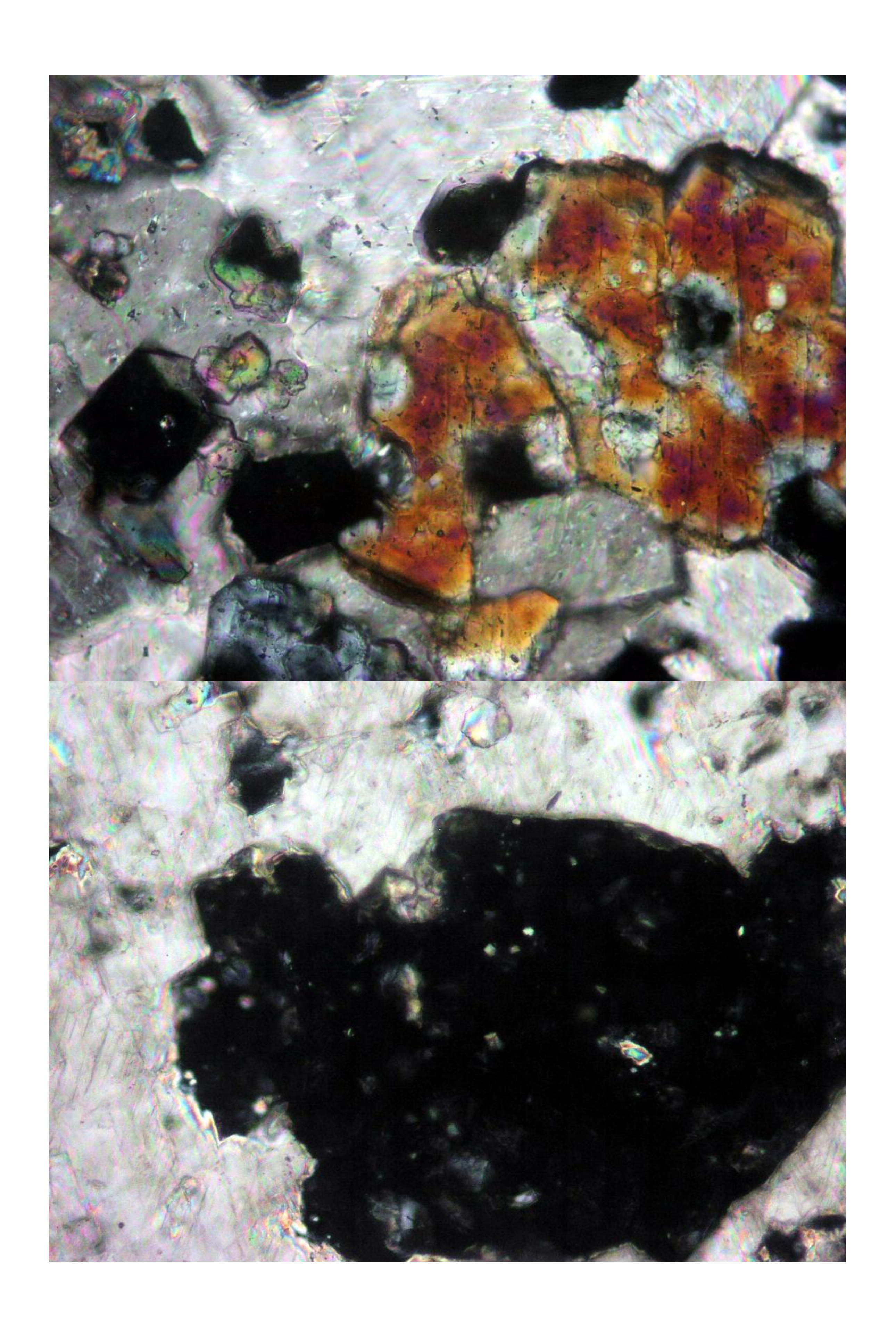
- The grade of metamorphism is function in grain size, where grain size increases with grade increase.
- At very HP, the polymorph aragonite becomes stable and aragonite marble is known from high pressure terrains.
- At HT/LP (>600°C) calcite and quartz react to produce wollasonite and CO_2. The reaction occurs only at high temperature thermal aureole, and is inhibited by high fluid pressures of CO_2.

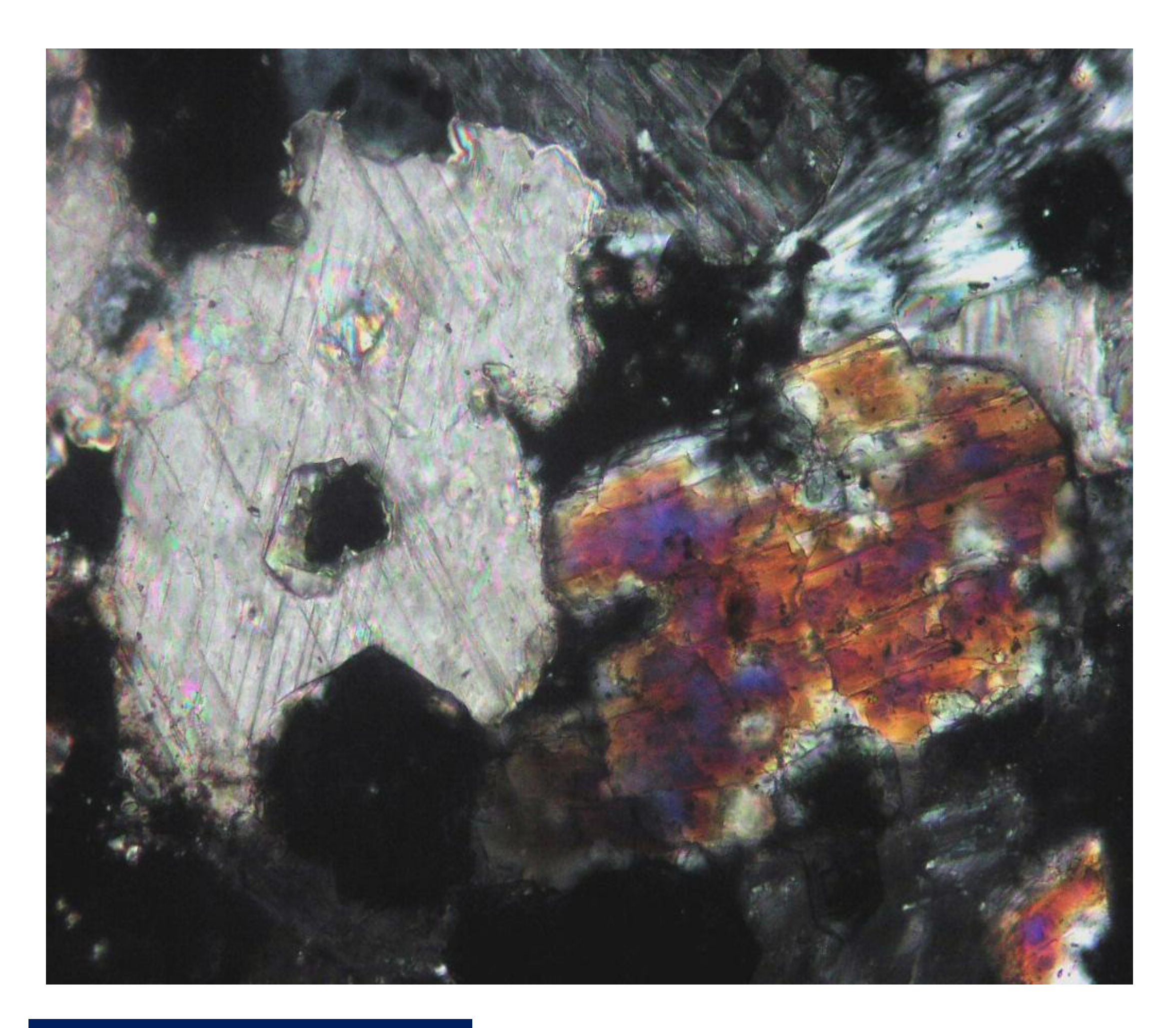
$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$











Dolomite marble, cont. :

Metamorphism of Dolomite:

Dolomite behaves like limestone when it is subjected to heat and pressure. It begins to recrystallize as the temperature rises. As this occurs, the size of the dolomite crystals in the rock increases and the rock develops a distinctly crystalline appearance.

If you examine the photo below, you will see that the rock is composed of easily recognizable dolomite crystals. The coarse crystalline texture is a sign of recrystallization, most often caused by metamorphism. Dolomite that has been transformed into a metamorphic rock is called "dolomitic marble."



Diopside and/or forsterite in the amphibolite facies:

tremolite+calcite+quartz = diopside+H_2O +CO_2

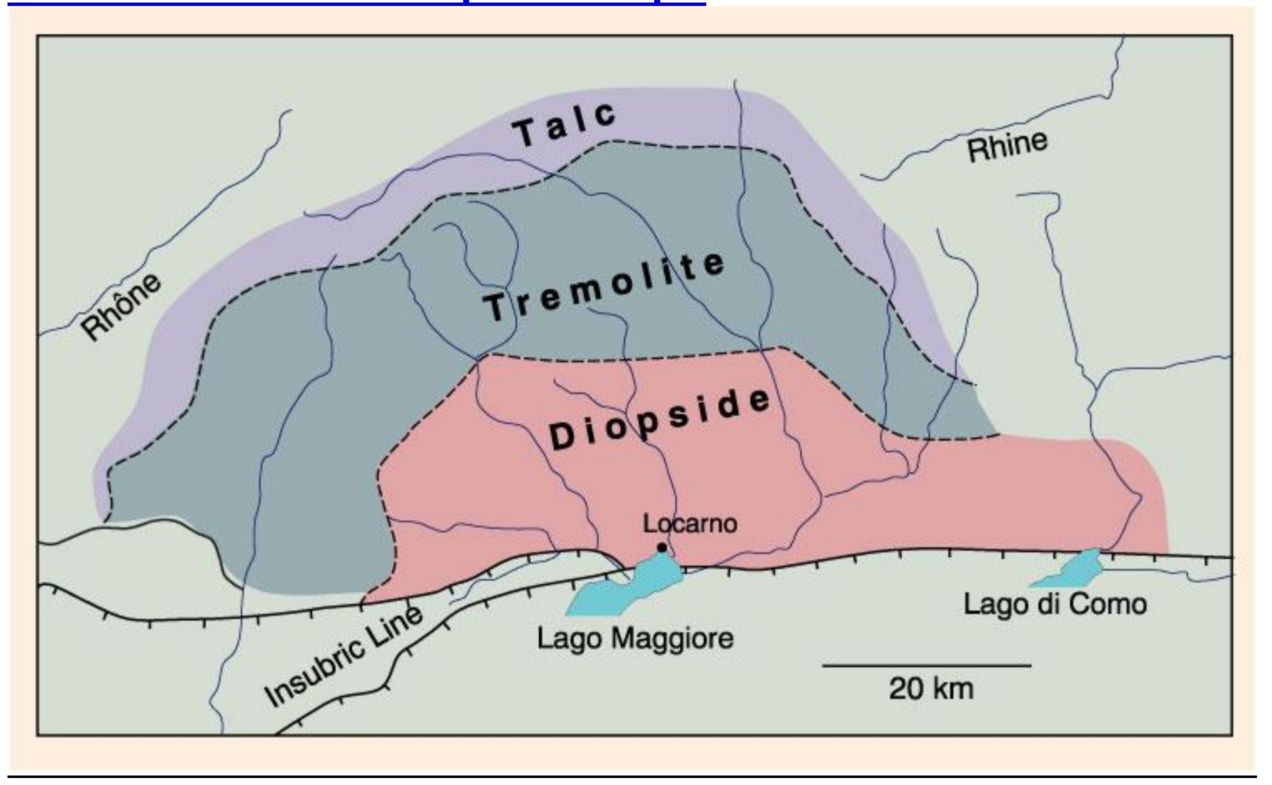
tremolite + dolomite = forsterite + calcite + H_2O + CO_2

Diopside + forsterite at higher grade:

tremolite + calcite = diopside + forsterite + H_2O+CO_2

- Sheet-silicate impurity in calcite and dolomite marble adds variety by the following Al-bearing minerals to feature in the assemblage: typically they include zoisite, epidote and Ca-rich garnet in the greenschist facies and anorthite in the amphibolite facies.

Metamorphic zones developed in regionally metamorphosed dolomitic rocks of the Lepontine Alps:



2-Metamorphism of impure carbonates and marls (Calc-silicates):

Calc-silicates:

- Calc-silicates are rocks rich in Ca-Mg-silicate minerals but poor in carbonate,
- They form via the metamorphism of very impure calcite or dolomite limestones, or from limy mudstones (marls).

Since calc–silicates contain significant amounts of other chemical components, such as Al, K and Fe, minerals such as zoisite (epidote group), garnet, Ca-plagioclase, K-feldspar, hornblende and diopside could formed. A generalized zonal sequence can be summarized as follows.

Amphibole zone:

The appearance of Ca-amphibole is accompanied by a further increase in the Ca content of the plagioclase:

Chl + Cal + Qtz + Pl ➔ Ca-amph



Zoisite zone:

Zoisite ($Ca_2(Al,Fe)_3[SiO_4](OH)$) often first appears rimming plagioclase at contacts with calcite grains, suggesting growth is due to the reaction:

Ca-plagioclase + calcite + H_2O ➔ zoisite + CO_2

Diopside zone:

At the highest grades diopside appears due to the breakdown of amphibole:

Ca-amphibole + calcite + quartz ➔ diopside + H_2O + CO_2

• **Calcareous**. Calcareous rocks are calcium rich. They are usually derivatives of carbonate rocks. At low grades of metamorphism calcareous rocks are recognized by their abundance of carbonate minerals like calcite and dolomite. With increasing grade of metamorphism these are replaced by minerals like brucite, phlogopite (Mg-rich biotite), chlorite, and tremolite. At even higher grades anhydrous minerals like diopside, forsterite, wollastonite, grossularite, and calcic plagioclase.

Pure limestone gives marble with granoblastic texture and crystals of calcite.

Impure limestone gives weak foliation at lower grade but at medium grade give calc-silicate rocks and amphibolite rocks at higher grade and composed of hornblende, diopside and Ca-plagioclase.

- Calcareous rocks are predominantly carbonates, usually limestone or dolostone
- Typically form in a stable continental shelf environment along a passive margin
- They may be pure carbonate, or they may contain variable amounts of other precipitates (such as chert or hematite) or detrital material (sand, clays, etc.)

Result when the passive margin becomes part of an orogenic belt which are often present.

Regional Calc-silicate:

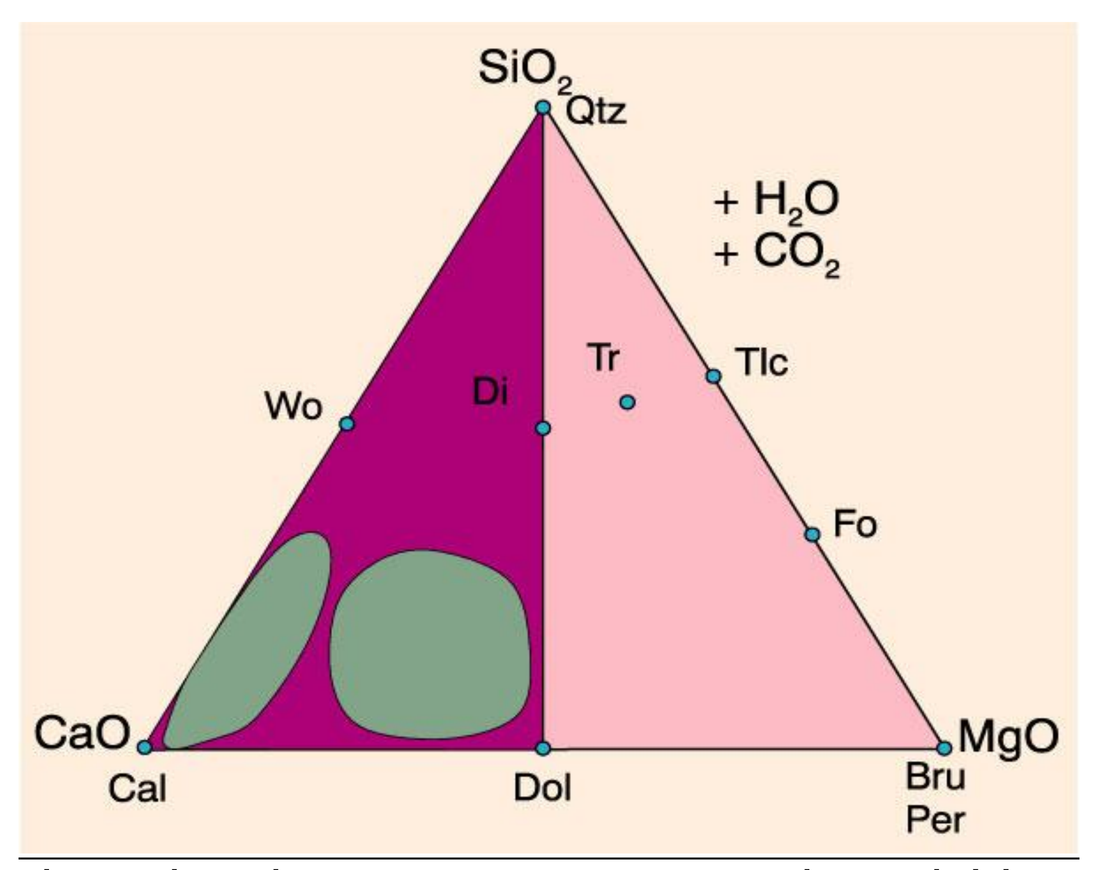
Sequence of appearance

- Talc (low X_{CO2}).
- Tremolite .
- Diopside .
- Forsterite .
- Wollastonite .

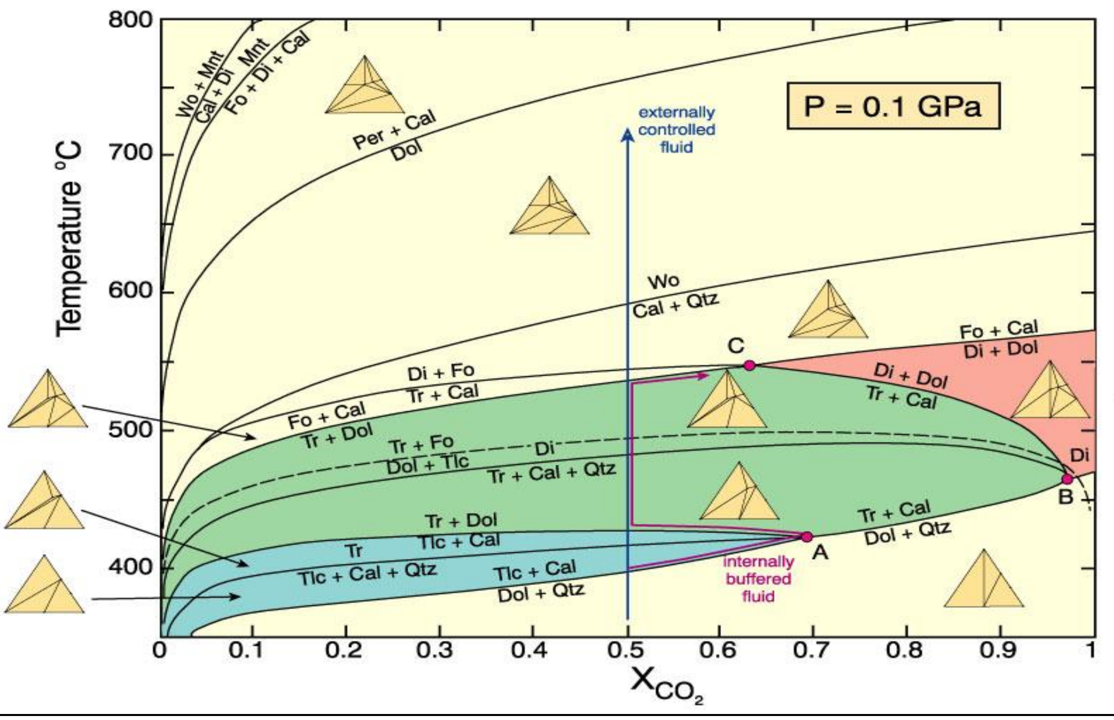


Skarns:

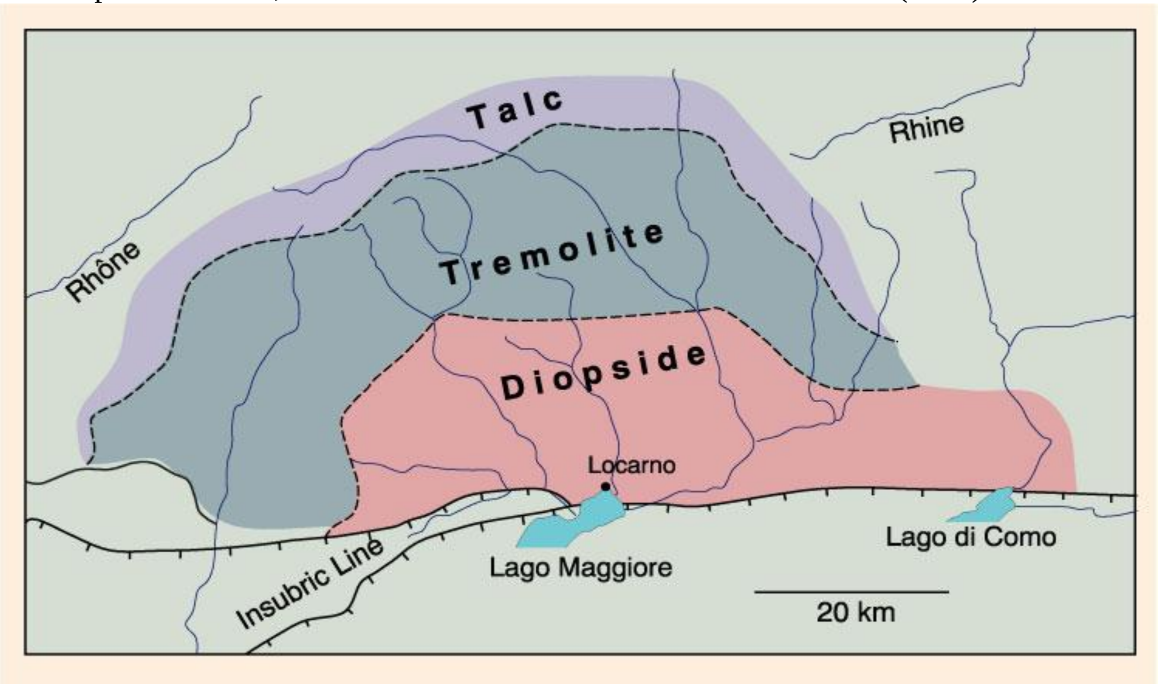
- Calc-silicate rocks formed by metasomatism
- Interaction between carbonates and silicate-rich rocks or fluids
- Contact between sedimentary layers
- Contact between carbonate country rocks and a hot, hydrous, silicate intrusion, such as a granite



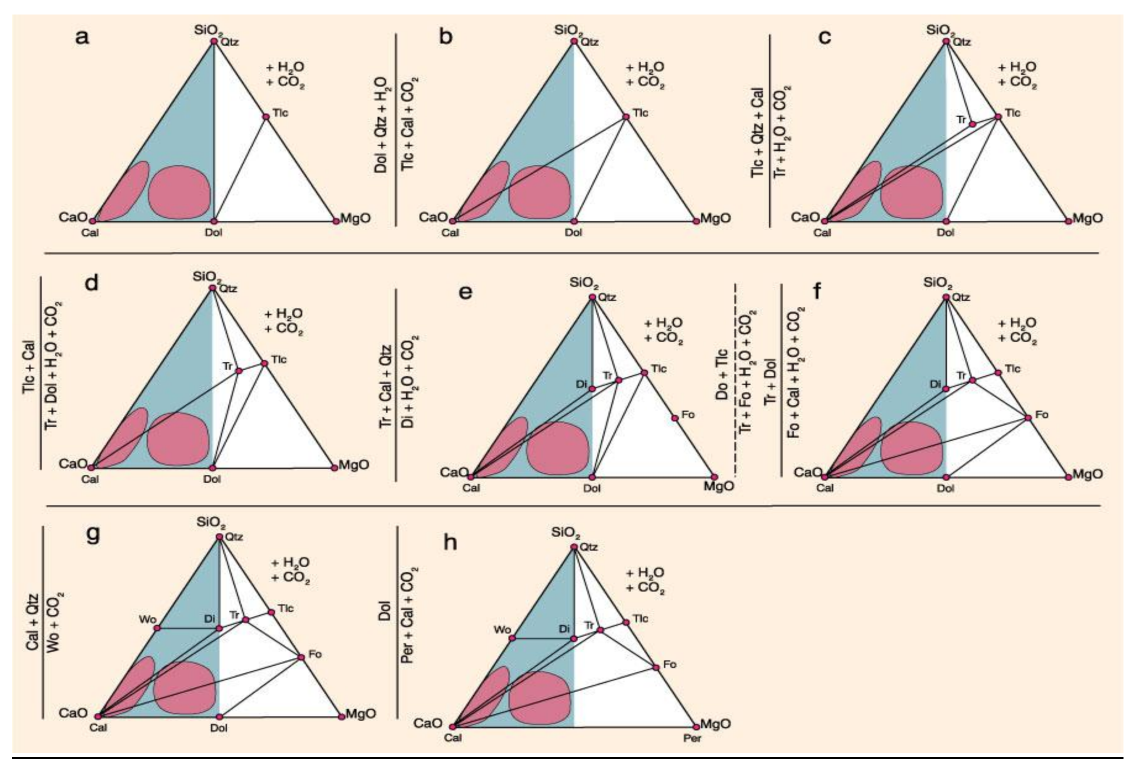
Chemographics in the CaO-MgO-SiO_2-CO_2-H_2O system. The green shaded areas represent common compositions of limestones and dolostones. Both calcite and dolomite can coexist in carbonate rocks. The left half of the triangle represents metacarbonates. Carbonated ultramafics occupy the right half of the triangle. Winter (2001).



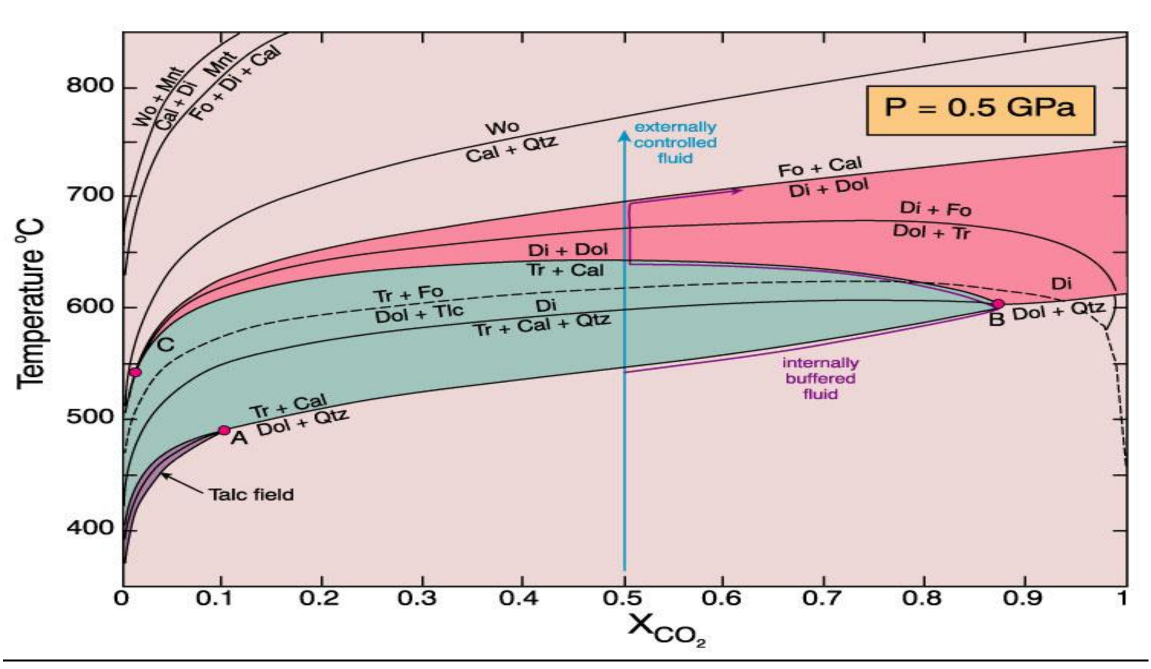
T-X_{CO2} phase diagram for siliceous carbonates at P = 0.1 GPa. The green area is the field in which tremolite is stable, the reddish area is the field in which dolomite + diopside is stable, and the blue area is for dolomite + talc. Winter (2001).



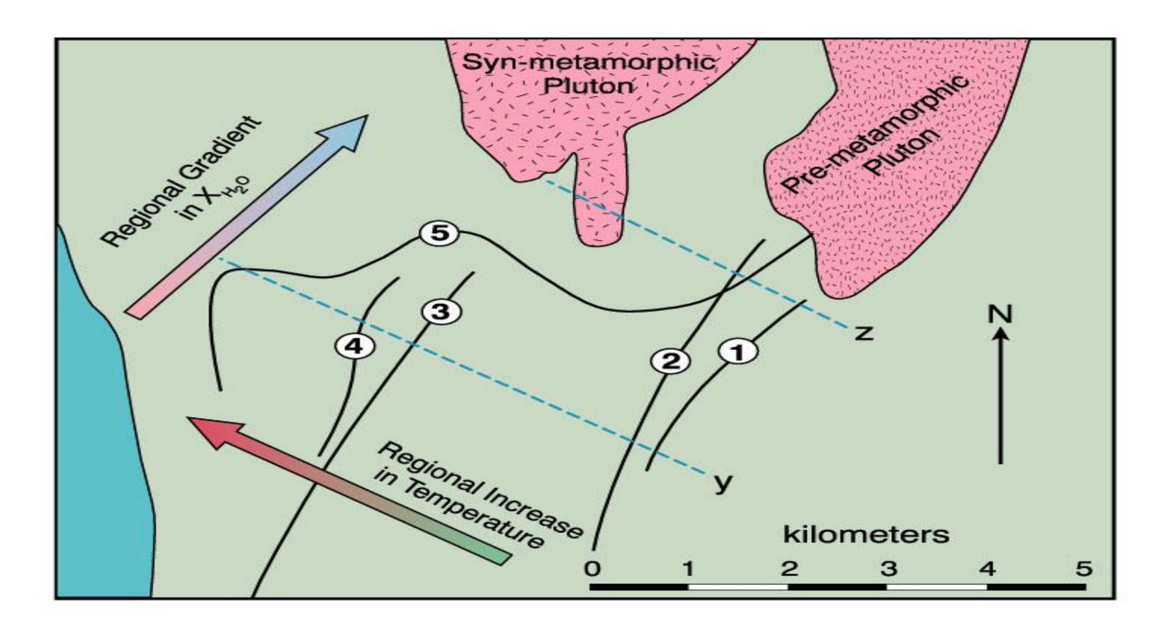
Metamorphic zones developed in regionally metamorphosed dolomitic rocks of the Lepontine Alps, along the Swiss-Italian border. After Trommsdorff (1966). Winter (2001).



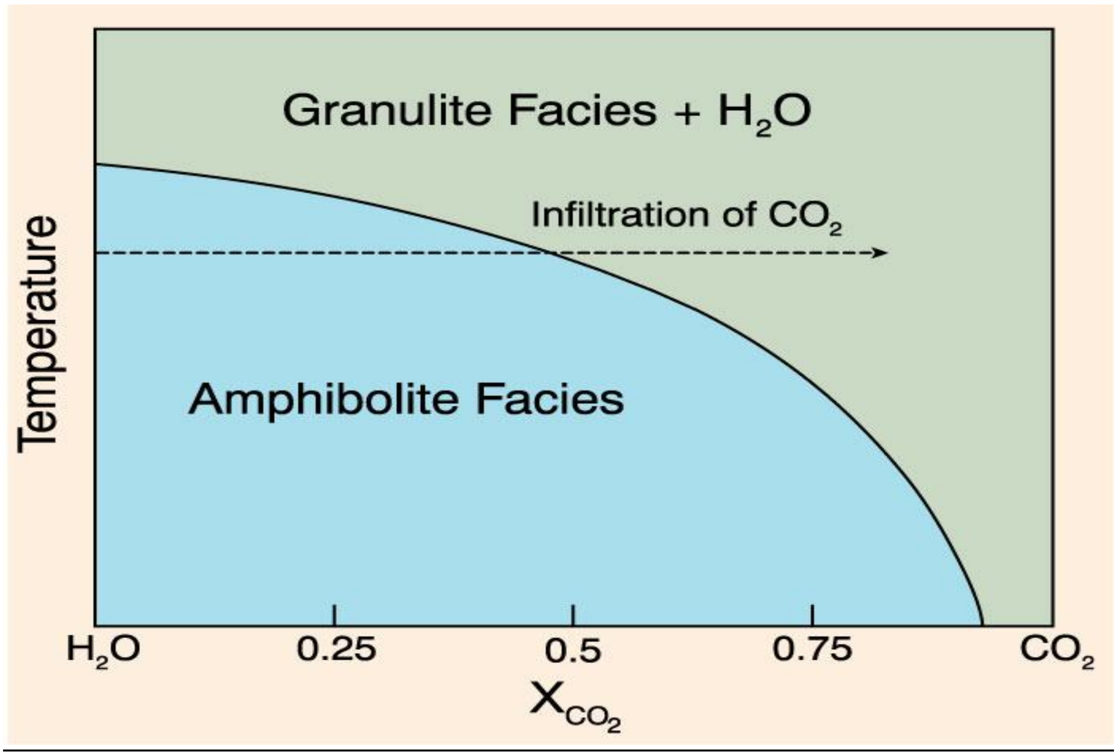
The sequence of CaO-MgO-SiO_2-H_2O-CO_2 compatibility diagrams for metamorphosed siliceous carbonates (shaded half) up metamorphic grade. The dashed isograd requires that tremolite is more abundant than either calcite or quartz. After Spear (1993)



T-X_{CO2} phase diagram for siliceous carbonates at P = 0.5 Gpa. The light-shaded area is the field in which tremolite is stable, the darker shaded areas are the fields in which talc or diopside are stable. Winter (2001).

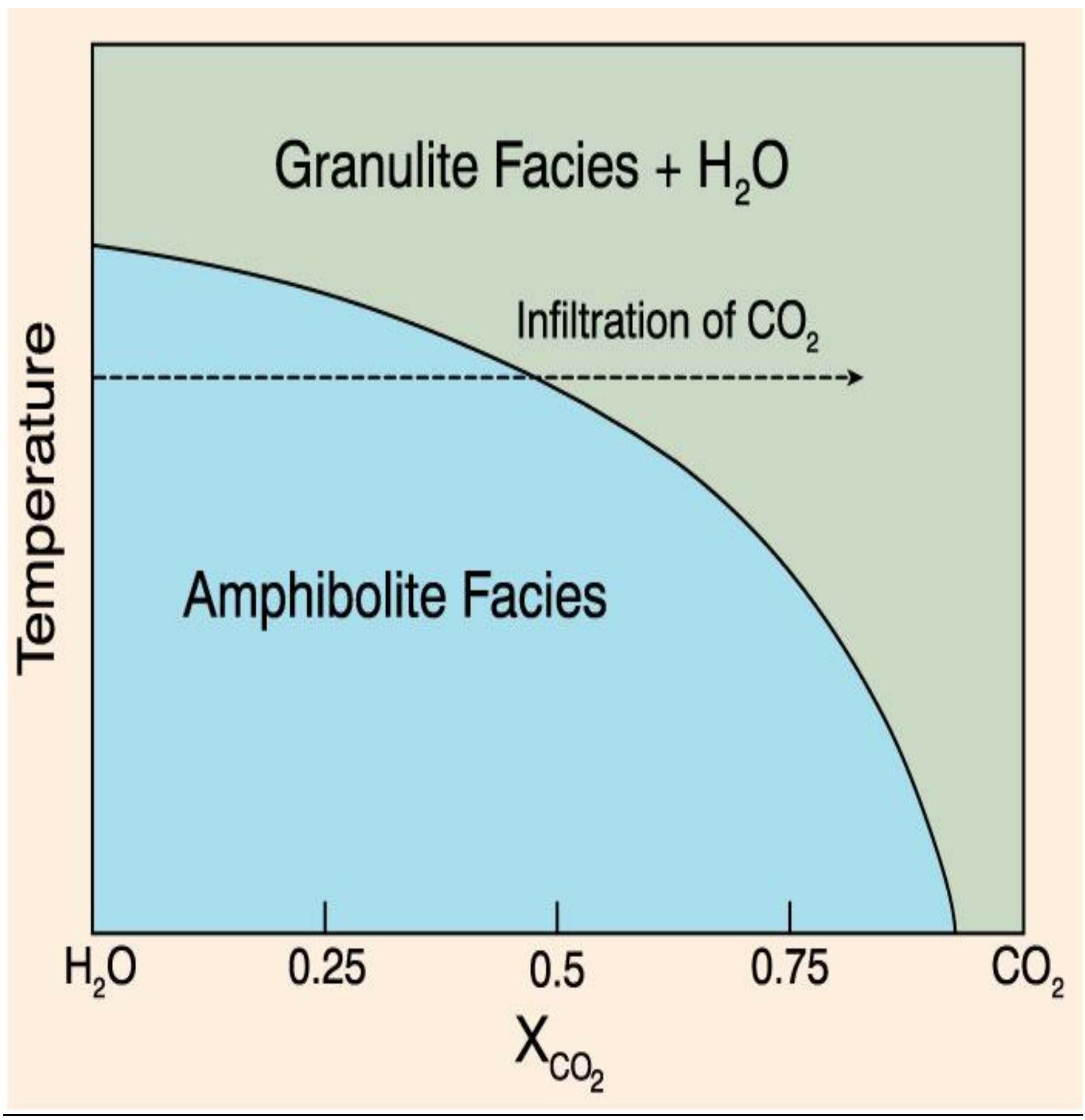


Isograds mapped in the field. Note that isograd (5) crosses the others. This behavior is attributed to infiltration of H_2O from the syn-metamorphic pluton in the area, creating a gradient in X_{H2O} across the area at a high angle to the regional temperature gradient, equivalent to the T-X diagram. After Carmichael (1970) *J. Petrol.*, 11, 147-181.



Schematic T-X_{CO2} diagram illustrating the characteristic shape of typical dehydration reactions, such as those that generate orthopyroxene from hornblende or biotite. Notice that the amphibolite facies to granulite facies can be accomplished by either an increase in temperature or infiltration of CO_2 at a constant temperature. Winter (2001)





Schematic T-X_{CO2} diagram illustrating the characteristic shape of typical dehydration reactions, such as those that generate orthopyroxene from hornblende or biotite. Notice that the amphibolite facies to granulite facies can be accomplished by either an increase in temperature or infiltration of CO_2 at a constant temperature. Winter (2001)

CHAPTER 11

Metamorphism of sandstone

Quartzite is sandstone that has been metamorphosed. Unlike sandstone, quartzite breaks through, not around, the quartz grains, producing a smooth surface instead of a rough and granular one. Quartzites are snowy white, less often pink or gray. They yield a thin and very barren soil and, because they weather slowly, tend to project as hills or mountain masses. Many prominent ridges in the Appalachian Mountains are composed of highly resistant tilted beds of quartzite.

The term quartzite implies not only a high degree of hardening (induration), or "welding," but also a high content of quartz. Most quartzites contain 90 percent or more quartz, but some contain 99 percent and are the largest and purest concentrations of silica in the Earth's crust. Pure quartzites are a source of silica for metallurgical purposes and for the manufacture of brick. Quartzite is also quarried for paving blocks, riprap, crushed stone, railroad ballast, and roofing granules.

In microscopic section the clastic structure of some quartzites is well preserved; the rounded sand grains are seen with quartz overgrowths deposited in crystalline continuity, so that optical properties of the grains are similar to those of the material surrounding them. In some cases a line of iron oxides may indicate the boundary of the original sand grain. Many quartzites, however, have been crushed, and the quartz largely is a mosaic of small, irregularly shaped crystalline fragments with interlocking margins.

Sandstones turn into quartzite in two different ways. The first way involves low pressure and temperature, where circulating fluids fill the spaces between sand grains with silica cement. When this rock is broken, the fractures go right through the original grains, not around them. This kind of quartzite, orthoquartzite, is not strictly speaking a metamorphic rock because the original mineral grains are still there, and bedding planes and other sedimentary structures are still evident.

Under the high pressures and temperatures of deep burial, the mineral grains recrystallize and all traces of the original sediments are erased. The result is a true metamorphic rock, called metaquartzite. This boulder is probably a metaquartzite.

Quartzite is a very strong stone but is difficult to work. Because quartzite has a limited color range and is not often found in large bodies suited for quarrying, the building industry prefers granite for demanding applications.



Three types of metamorphism may occur depending on the relative effect of mechanical and chemical changes. Dynamic metamorphism, or cataclasis, results mainly from mechanical deformation with little long-term temperature change. Textures produced by such adjustments range from breccias composed of angular, shattered rock fragments to very fine-grained, granulated or powdered rocks with obvious foliation and lineation termed mylonites. Contact metamorphism occurs primarily as a consequence of increases in temperature where differential stress is minor.

Metamorphism due to collision and subducted tectonic plates:

When an oceanic crust subducted under island arc or old continent, the subducted plate will metamorphosed to eclogite rocks but at the trench or accretonay wedge, the converging and collision of the two plate yields high pressure manifested by folding, faulting and crushing under high pressure and low temperature giving blue-schist facies. Thin layer (upper part composed of marin muds and altered basalt of subducted plate) suffer partial melting and so intermediate magma of granitiod-diorite composition will elevated to the lower crust and affected the intruded rocks by high temperature giving metamorphic rocks of high temperature and low pressure back old island arc. So between the high pressures metamorphic rock at trench and high temperature metamorphic rock back arc, there is a gab called **Arc-trench gab**. This is found in recent converging plate but the old converging belts resulted to collision of two metamorphic belts adjacent to each other due to continuous subduction and thrusting of belts. In this case there is a paired metamorphic belts (high pressure and high temperature) called **"paired metamorphic belts"** of blue-schist in contact with thermal metamorphic rocks. **The eclogite** rocks are formed along the lower part of subducted plate (high temperature and very high pressure).

CHAPTER 12

Metamorphism of Spilitic basalt

Metamorphism of basalt:

Basalts are important rocks within metamorphic belts, as they can provide vital information on the conditions of metamorphism within the belt. Various metamorphic facies are named after the mineral assemblages and rock types formed by subjecting basalts to the temperatures and pressures of the metamorphic event. These are:

- Blueschist facies
- Eclogite facies
- Granulite facies
- Greenschist facies
- Zeolite facies

Metamorphosed basalts are important hosts for a variety of hydrothermal ore deposits, including gold deposits, copper deposits, volcanogenic massive sulfide ore deposits and others.

The oceanic crust is formed of basalt highly altered by sea water. The alteration results in addition of H2O and Na to the basaltic rocks and subtraction of Ca, Si from basalt to sea water this metasomatic rocks are called spilite.

Oceanic basalt of subducted plate converted to eclogite rocks under high pressure and comosed of Mg-pyrope granite (red) and green omphacite (Na-rich pyroxene).

Metamorphism of Ultramafic Rocks:

- **Alpine peridotites :**

– Uppermost mantle = base of slivers of oceanic lithosphere that become incorporated into the continental crust along subduction zones

- **Dismembered portions of ophiolites :**

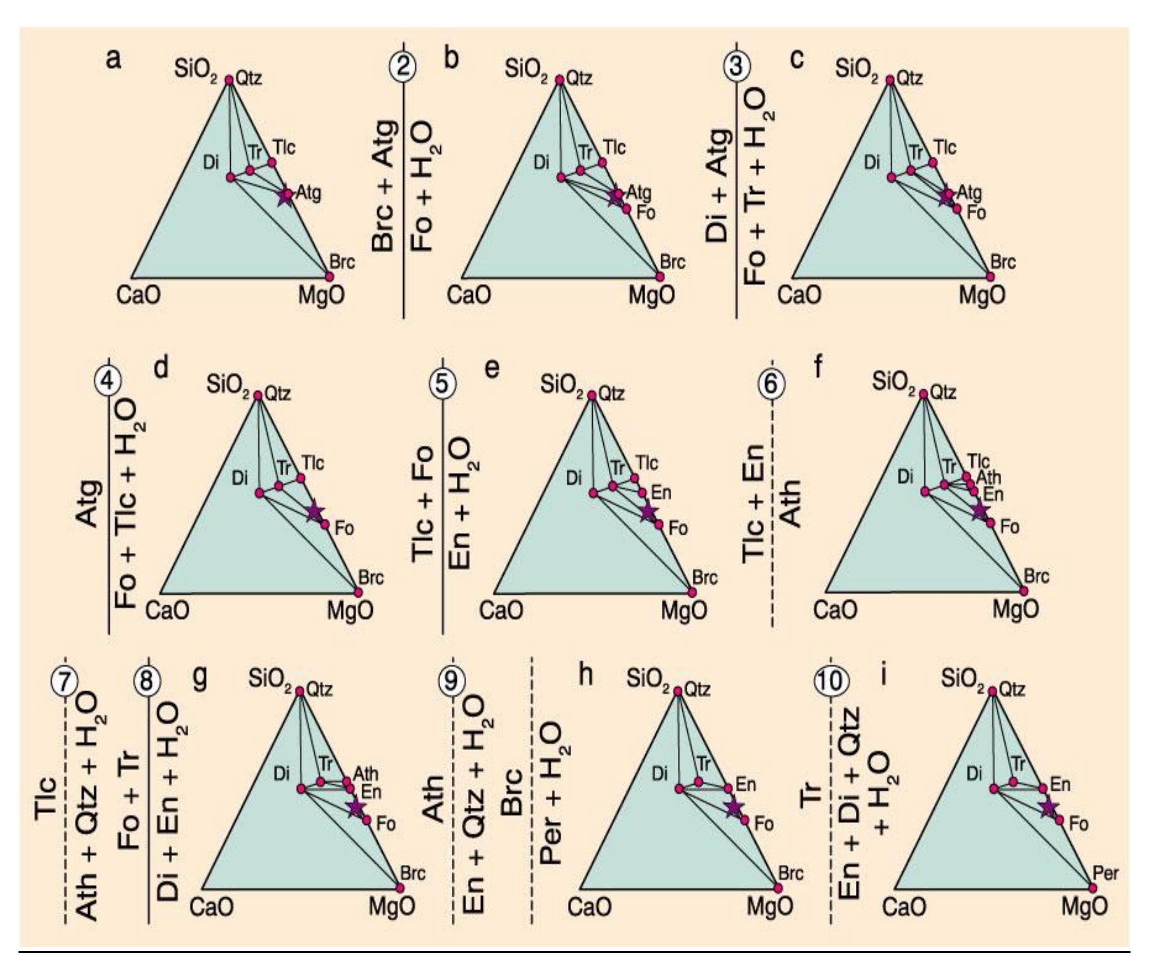
– Pieces of oceanic crust and mantle that either separate from the subducting slab and become incorporated into the accretionary wedge of the subduction zone,

– Or (more commonly) get trapped between two terrains during an accretion event

Associations :

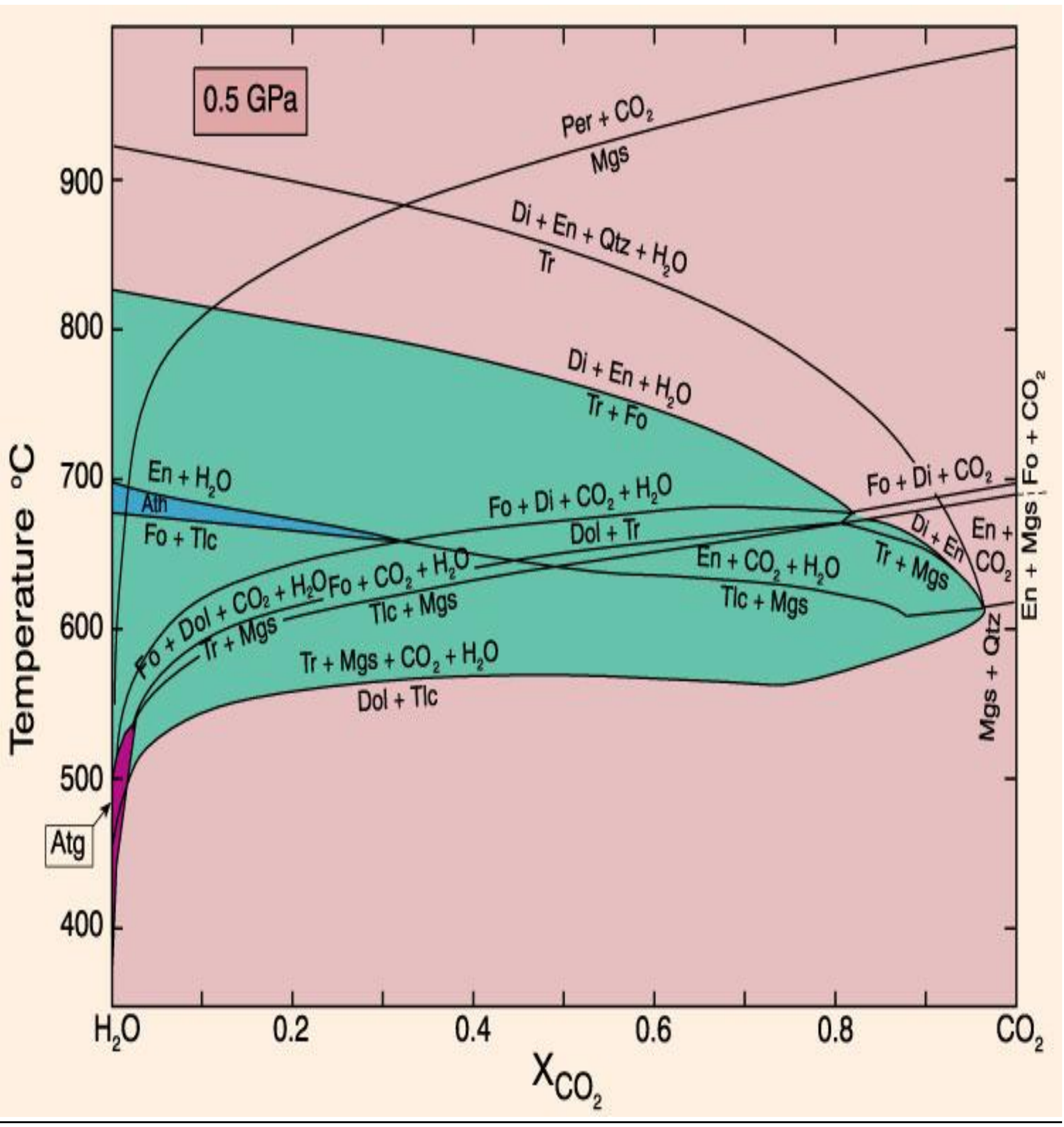
- Strings of ultramafic bodies in orogens follow major fault zones separating contrasting rock bodies. Interpreted as remnants of oceanic crust + mantle that once separated collisional terranes, and thus mark the suture zone

- Association of blueschist facies rocks with the ultramafics further supports a subduction-related origin.





Chemographics of ultramafic rocks in the CMS-H system (projected from H_2O) showing the stable mineral assemblages (in the presence of excess H_2O) and changes in topology due to reactions along a medium P/T metamorphic field gradient. The star represents the composition of a typical mantle lherzolite. After Spear (1993).



Shaded fields represent the stability ranges of serpentine-antigorite (purple), anthophyllite in low-SiO_2 ultramT-X_{CO2} phase diagram for the system CaO-MgO-SiO_2-H_2O-CO_2 at 0.5 Gpa. Focuses on ultramafic-carbonate rocksafics (blue), and tremolite in low-SiO_2 ultramafics (green). Winter (2001).

Metamorphism of Mafic Rocks:

• The general term basic refers to low silica content. Basic metamorphic rocks are generally derivatives of basic igneous rocks like basalts and gabbros. They have an abundance of Fe-Mg minerals like biotite, chlorite, and hornblende, as well as calcic minerals like plagioclase and epidote

. **• Magnesian Rocks** that are rich in Mg with relatively less Fe, are termed magnesian. Such rocks would contain Mg-rich minerals like serpentine, brucite, talc, dolomite, and tremolite. In general, such rocks usually have an ultrabasic protolith, like peridotite, dunite, or pyroxenite.

Carbonatite Deposits

The metamorphic system can also react differently if fluids are part of the system. Serpentinite, a mottled green rock, is usually formed with high pressure and low temperature. The original rock could contain a large amount of olivine (i.e., basalt). The **olivine** (Mg_2SiO_4) reacts with water (H_2O) to form the mineral serpentine ($Mg_3Si_2O_5(OH)_4$)plus magnesium oxide (MgO).



Serpentinite is found in areas where faulting occurs. Along the San Andreas fault zone in California, serpentinite is so abundant it is recognized as the California state rock. The pressure of **shearing** seems to be ideal for the serpentinite to form a fibrous pattern. This form of serpentinite is a variety of asbestos, which is used as a fire retardant.

CHAPTER 13

Metamorphism and Tectonics

An overview of metamorphism in relation to tectonic regimes:

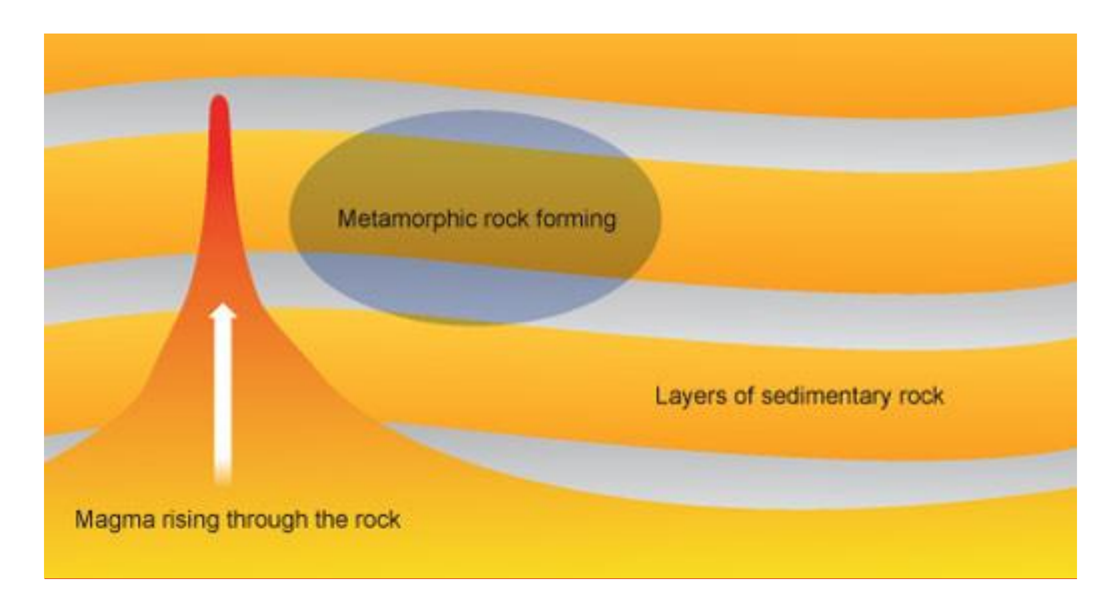
The metamorphic facies series encountered in different tectonic regimes or settings can be summarized as follows

contact and →(a) Ridges and rift valleys: characterized by high geothermal gradients ocean floor metamorphism.

→(b) Areas of magmatic activity; volcanic - plutonic complexes: greenschists amphibolites →(c) Areas of crustal thickening and mountain building: greenschists granulites→

and type B eclogites (particularly if there are magmatic intrusions).

→(d) Subduction zones: Characterized by low geothermal gradients: zeolite type C → blueschist facies →pumpellyite-actinolite facies /lawsonite albite facies eclogites.



A- Convergent Plate Boundarie:

I- Subduction Zone metamorphism:

Rocks of the subducted plate are usually metamorphosed following "clockwise" P-T paths in which peak pressures are attained before peak temperatures. According to tectonic setting, subduction is of two "types":



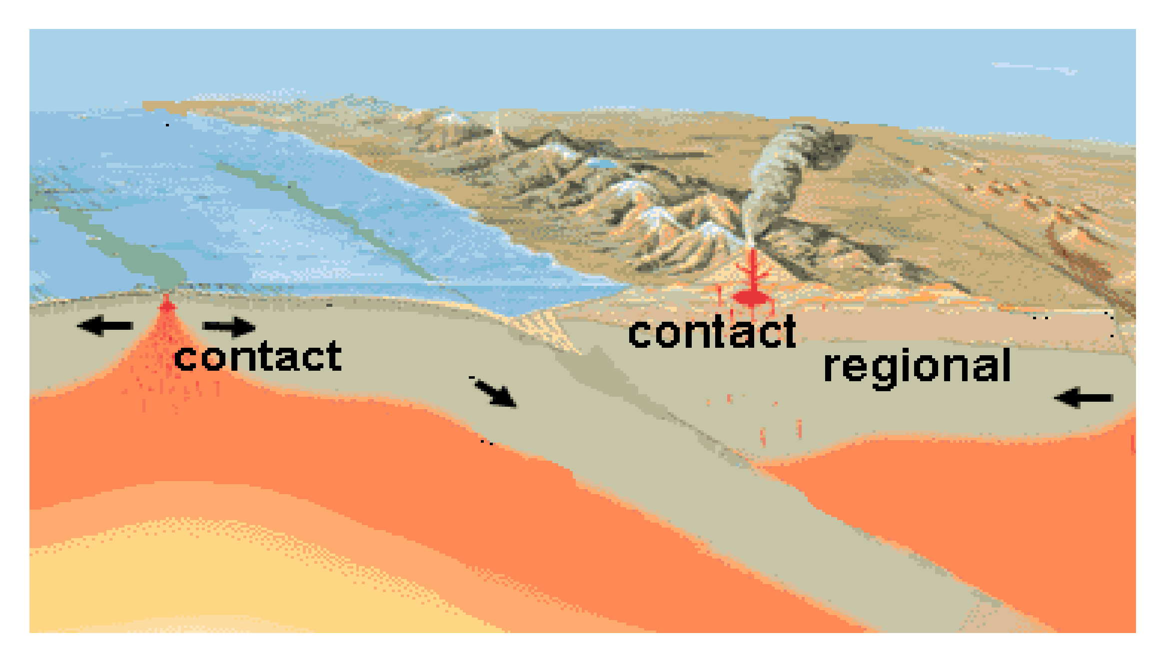
(a) B-type subduction: where the oceanic crust is subducted beneath a continental or another oceanic plate. This type usually results in the formation of the "paired metamorphic belts" of Miyashiro, with blueschists and eclogites in the subducted plate close to the subduction thrust, and high T, low P amphibolite- and sandinite- facies rocks on the overriding plate, commonly forming an island arc in the case of ocean - ocean interaction (Figs. 3 and 4). Examples of this type include the Franciscan (with the Sierra Nevada) in the western U.S.A., and the Sanbagawa (and Abukuma) belts in Japan.

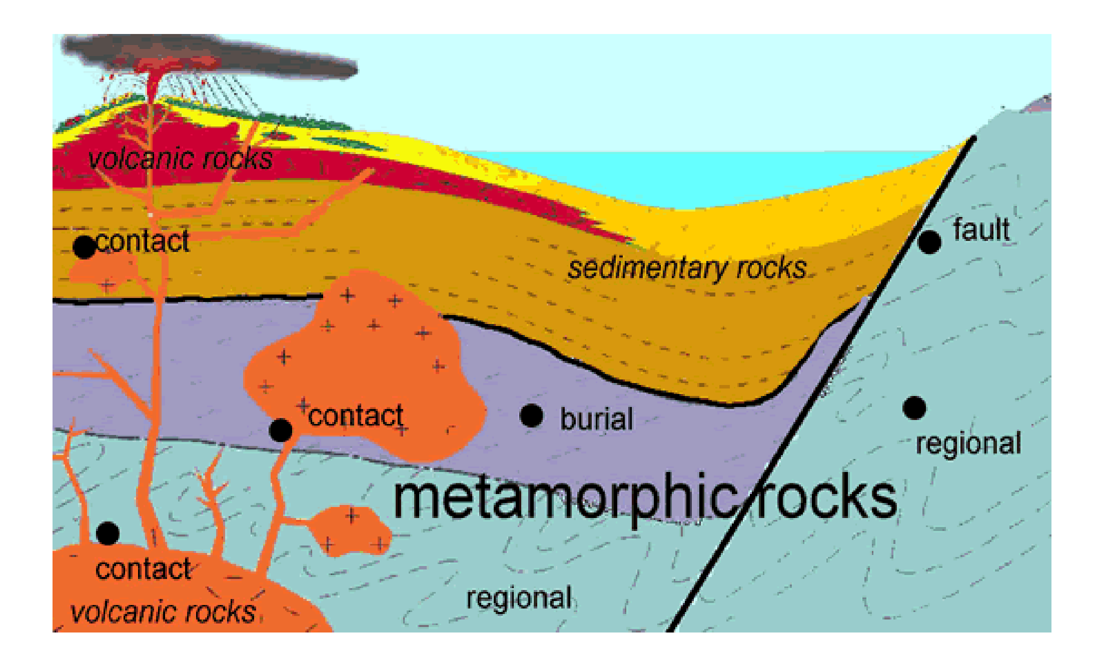
(b) A-type subduction: where the continental crust "attempts" to become subducted usually beneath another continental plate. Because of the low density of continental material, it is generally more difficult to subduct compared to the oceanic crust, and will have a tendency to "rebound" isostatically. Examples include the western Alps (Dora Maira), the Tauern Window (Austrian Alps), and Saih Hatat (Oman).

While discussing subduction zone metamorphism, it is appropriate to discuss some of the problems associated with its rocks. The most important of these is the preservation of blueschist facies mineral assemblages, and the uplift of blueschists.

There are several ways that metamorphic rocks form at or near plate boundaries. There is localized metamorphism called **contact metamorphism**. Usually this occurs near molten magma or lava, under high temperature and low pressure. Metamorphism affecting a large area or **regional metamorphism** involves large increases of temperature and pressure. Contact metamorphism is common at both **convergent** and **divergent** plate boundaries, in areas where molten rock is produced. Regional metamorphism largely occurs at convergent plate boundaries.

Each of these types of metamorphism produces typical metamorphic rocks, but they may occur in different sequences. For example, both regional and contact metamorphism produce schists and shales. However, gneiss would be common in regional metamorphism.





Preservation of Blueschists:

- Most blueschists (and type C eclogites) are characterized by clockwise P-T paths, and may therefore undergo heating and decompression during their exhumation.
- If the geothermal gradient prevailing during exhumation is sufficiently high, these rocks will pass through the greenschist, epidote amphibolite or amphibolite facies upon exhumation.
- If exhumation rate is not rapid enough, these rocks will be overprinted by these later assemblages to such an extent that they may not survive their trip to the surface.
- Draper and Bone (1974) suggested that the preservation of blueschists requires exhumation rates that cannot be accounted for by average erosional rates.
- Hairpin shaped paths and their significance ⇒ underthrusting and refrigeration.

Models of blueschist and eclogite exhumation:

a) Platt's model: Platt (1987) suggested that blueschists and type C eclogites formed by B-type subduction may be underplated (attached or accreted) to the overriding plate or mantle wedge. Such process leads the accretionary wedge to become thicker and tectonically unstable. This in turn leads to the development of normal faults along which the high P/T rocks can make their way back to the surface fairly rapidly without being significantly overprinted model can be tailored to type A subduction zones.

b) Cloos's model: Cloos (1982) suggested that during B-type subduction, accretionary wedge pelitic material moving down the subduction zone will tend to flow back upwards by the forces of buoyancy, when it can then carry bits and pieces of the subducted slab (now metamorphosed under blueschist and eclogite facies conditions. This model works only for tectonic mélanges, such as in the Franciscan.



c) Other models: Water melon seed model; delamination; …. etc.

Blueschists in time:

Most blueschists are Mesozoic in age, with some Paleozoic examples, and only a handful of Precambrian ones. Could this be due to Plate tectonics not operating during the Precambrian the way we think it does today? Or is it a function of differences in geotherms prevailing at those times? Post-Eocene blueschists are also very rare or non-existent. Can you think of a reason?

II- Thrusting and continent - continent collision:

Not all areas of continent – continent collision are characterized by high P/T metamorphism; many were found to belong to Miyashiro's high P, intermediate facies series; whereas others are associated with so much magmatic activity that they may be considered to belong to the "regional – contact" type of metamorphism of Spear (1993). Examples of these two cases include:

1- The Himalayas (which have an inverted metamorphic gradient in which the Sill zone overlies the Ky zone, which in turn overlies the Gt and Bt zones . Several models have been proposed to explain this inverted sequence and the P-T paths obtained.

2- New England: The northern Appalachians are characterized by a complex Polymetamorphic history. The main event seems to have been Acadian, in which a continental fragment collided with N. America resulting in partial melting and the development of numerous igneous intrusions. Nappes containing sheet – like igneous intrusions were emplaced onto colder sheets. The overthrust nappes therefore had counterclockwise P-T paths, whereas the lower nappes were characterized by periods of isobaric heating followed by near isothermal loading).

III- Metamorphism associated with ophiolite emplacement:

1- Subophiolitic metamorphic aureoles or soles and inverted metamorphic gradients.
2- Burial type metamorphism with a high P/T field gradient
3- Subduction zone metamorphism

B- Stable continental interiors and deep sedimentary basins:

These are characterized by burial metamorphism with clockwise P-T paths, and peak T in the greenschist to epidote amphibolite facies.



C- Divergent Plate Boundaries:

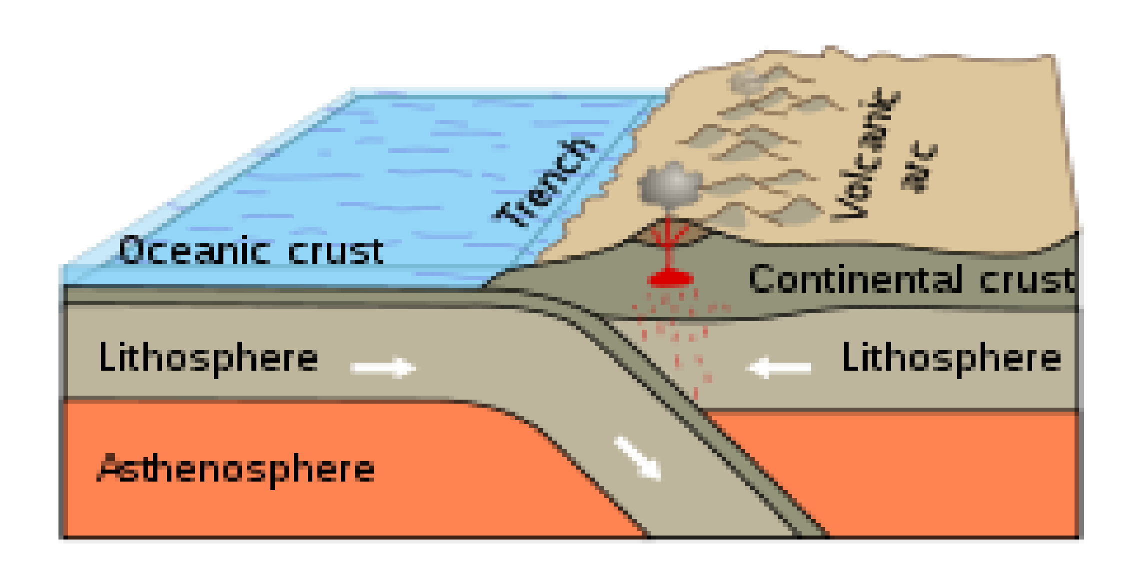
1- Ocean Floor Metamorphism:

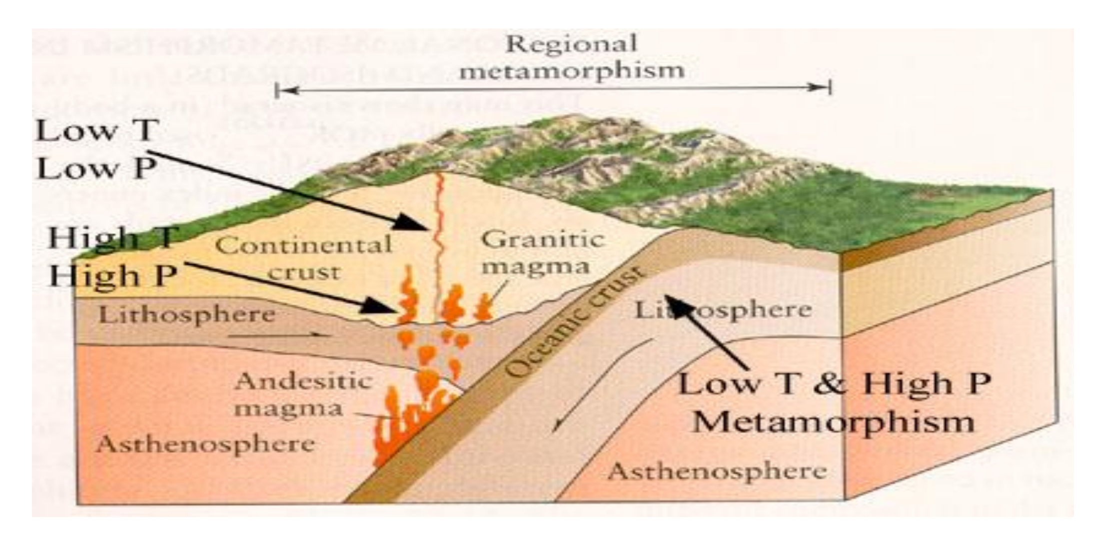
2- Continental rifts: In such settings, it is very common to find "metamorphic core complexes", defined as areas that are topographically high and that consist of igneous and metamorphic rocks that display anomalous deformation and metamorphism relative to the surrounding rocks. These complexes are structurally overlain by normally faulted sedimentary rocks. The boundary between the complexes and the sedimentary rocks is a low angle normal fault known as a "decollement". Rocks of the metamorphic core complex are characterized by clockwise P-T paths of evolution, with segments of isothermal decompression, marking their rapid exhumation along these decollements. Examples include several areas in the Basin and Range province, and the Cordillera Darwin in Chile.

Conservative Plate Boundaries:

1- Cataclasis and Mylonitization

2- Serpentinite diapirs and associated metasomatism.





التحول وتكتونية الألواح:

إن أحد النجاحات التي أحرزتها نظرية تكتونية الألواح، أنها أمدتنا للمرة الأولى بتفسير لتوزيع نطاقات الصخور المتحولة في الصخور المتحولة إقليميا. وقد أوضحنا عند بداية هذا الفصل العلاقة بين الأوضاع التكتونية المختلفة والعمليات الجيولوجية (مثل النشاط البركاني ونشأة الجبال) التي تسبب الأنواع المختلفة . كما يمكننا أيضا أن نستنتج موقع الصخر في التحول، على أساس رتبة التحول والتركيب.

وترتبط صخور الحجر الأخضر، والتي تنتج عن تحول صخور نارية مافية مثل صخور البازلت والجابرو بالتحول الحرمائي عند حيود وسط المحيط أثناء تباعد الألواح.

فعندما يحدث انتشار لقيعان المحيطات وتصعد الصهارة البازلتية من الوشاح تحول حرارة الصهارة صخور البازلت المنبثقة حديثا في وجود الماء إلي صخور متحولة ذات رتبة تحول منخفضة تتبع سحنة الشست الأخضر.

ويلعب دوران السوائل الحرمائية خلال البازلت دورا مهماً في تحول صخور البازلت، حيث يتفاعل الماء مع المعادن اللامائية وتتكون معادن مافية مثل الكلوريت والسربنتين. كما يحل الصوديوم الموجود في الماء محل الكالسيوم في معدن البلاجيوكليز الموجود في صخور البازلت.

أن التحول الإقليمي يكون عند حد الاندساس للوح الهابط أثناء تقارب الألواح.

فعندما تهبط الصخور المتبلورة لأسفل باللوح المندس بسرعة (نحو 1سم / عام) فإن الضغط يزداد تحت تلك الظروف عن درجة الحرارة بسرعة، ويتعرض الصخر لضغط عال ودرجة حرارة منخفضة نسبيا، وهى الضغوط ودرجات الحرارة المميزة لسحنة الشست الأزرق.

ومن المحتمل أن تحول الشست الأزرق يحدث حاليا على امتداد الحافة الهابطة للوح الهادىء، حيث يندس تحت شاطيء الأسكا وجزر اليوشان. ويتكون عند أعماق أكبر سحنة الإكلوجيت حيث تكون درجة الحرارة أكثر ارتفاعا.

وتتواجد الظروف المميزة لسحنتي السشت الأخضر والأمفيبوليت عندما يزيد سمك القشرة القارية نتيجة التصادم القاري، أو ارتفاع درجة الحرارة بواسطة الصهارة الصاعدة.

ويعتبر التصادم القاري أكثر مناطق التحول الإقليمي شيوعا، حيث يمكن رؤية مساحات عريضة من الصخور المتحولة إقليميا في جبال الأبلاش والألب.

كما يتميز عديد من المناطق في مصر والمملكة العربية السعودية بوجود عدة مناطق متحولة إقليميا مثل منطقة حفافيت بالصحراء الشرقية المصرية ووادي فيران ووادي الشيخ بسيناء.

ويحدث مثل هذا التحول حاليا تحت جبال الهيمالايا، حيث يزداد سمك القشرة القارية نتيجة التصادم،وتحت جبال الأنديز حيث يزداد سمك القشرة الأرضية وترتفع درجة حرارتها من الصهارة الصاعدة.

أما الأجزاء العميقة من القشرة القارية، فإنها تسخن وتتحول إلي رتب مختلفة نتيجة تصادم القارات وزيادة سمك الغلاف الصخري، بينما يبدأ الانصهار الجزئي الرطب في النطاقات الأعمق حيث تتكون صخور الميجماتيت، وقد تستمر العملية لتصل إلي الانصهار الكامل وتكون الصهارة.



وبهذه الطريقة ينشأ خليط معقد من الصخور المتحولة والنارية في لب أحزمـة التجبل، التـي تنشأ خلال عمليـة تكون الجبال. وعندما تقوم التعرية بإزالة الطبقات السطحية بعد ملايين السنين، ينكشف لب أحزمة الجبال على السطح، مما يؤدي إلي إمداد الجيولوجيين بسجل صخري لعمليات التحول التي كونت الشست والنيس وصخور متحولة أخرى.

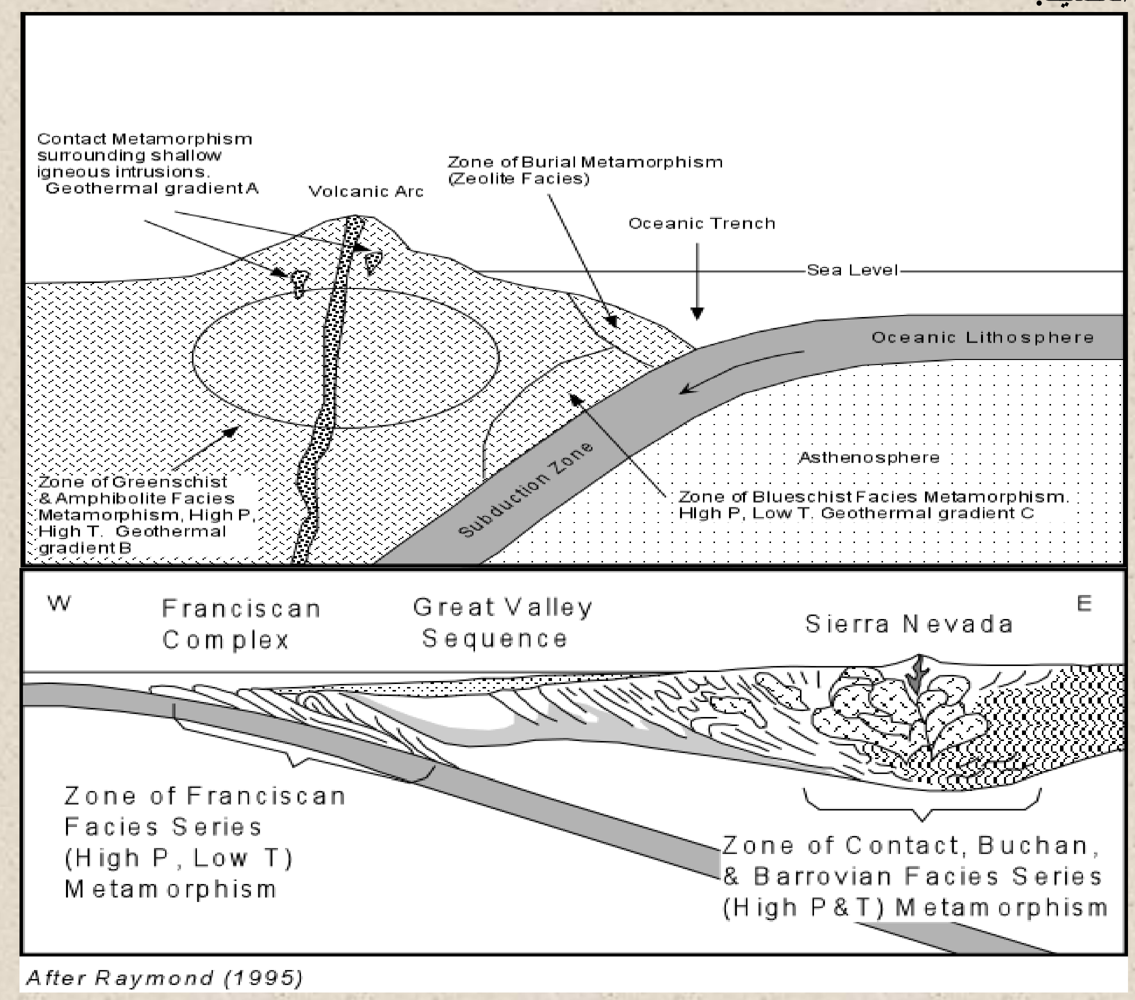
وترتبط أيضا عمليـة التحـوال ونشأة المحاليل الحرمائيـة بتكتونيـة الألـواح، نظرا لأن التحوال يرتبط بـالتحول الإقليمي والنشاط الصهاري.

ويوضح شكل (19 – 11) مثـالا لتوزيـع رواسـب النحـاس الغنيـة بمعدن الكالكوبيريـت فـي أمريكـا الشـمالية والجنوبية، حيث يمكن تمييز حزام من الرواسب المعدنية المتكونة في / أو مرتبطة ببراكين طباقية قديمـة تمتـد على الحافة الغربية للأمريكتين.

وقد نشأت الصهارات التي كونت البـراكين الطباقيـة نتيجـة للانصـهار الجزئـي الرطب لقشرة محيطيـة مندسـة، بالإضافة إلي صخور الوشاح المتواجدة فوقها. كما كانت الصهارات مصدرا لحرارة المحاليل الحرمائيـة، والتـي أدت إلي تحول تلك الصخور المجاورة لها، والتي انسابت خلالها المحاليل لتكون رواسب الخامات.

كما يوجد التحول الحرمـائي مصاحبا لمراكز الانتشار أيضا عند حيود وسط المحيط أي عند حواف القـارات المتباعدة.

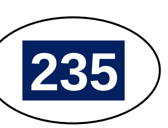
ويعتقد أن التحول بالدفن يوجد في الأجزاء السفلى من التراكمات السميكة للرواسب التي تتراكم على الرفوف والمنحدرات القارية. ومن المعروف أن مثل هذا التحـول يحدث اليوم في التراكم الضـخم للرواسب فـي خلـيج المكسيك.



After Raymond (1995)

References

- Bucher, Kurt, 2002, *Petrogenesis of Metamorphic Rock,* Springer.
- Eskola P., 1920, *The Mineral Facies of Rocks*, Norsk. Geol. Tidsskr., 6, 143-194.
- Gillen, Cornerlius, 1982, *Metamorphic Geology : an Introduction to Tectonic and Metamorphic Processes*, London; Boston: G. Allen & Unwin ISBN 978-0045510580.
- Marshak, Stephen, 2009, *Essentials of Geology*, W. W. Norton & Company, 3rd ed. ISBN 978-0393196566.
- Vernon, R. H., 1976, *Metamorphic Processes,* Halsted Press.
- Vernon, Ronald Holden, 2008, *Principles of Metamorphic Petrology,* Cambridge University Press ISBN 978-0521871785.
- Phillpots, Anthony R., 1990: *Principles of Igneous and Metamorphic Petrology* .
- Duff, P. McL. D., 1996; *Holmes' Principles of Physical Geology* .
- Visser, W.A., 1980; *Geological Nomenclature*}} .
- Metamorphic facies by Dave Waters .
- Ballhaus, C.G. & Glikson, A.Y., 1995, Petrology of layered mafic-ultramafic intrusions of the Giles Complex, western Musgrave Block, central Australia. AGSO Journal, 16/1&2: 69-90.
- Hill R.E.T, Barnes S.J., Gole M.J., and Dowling S.E., 1990. Physical volcanology of komatiites; A field guide to the komatiites of the Norseman-Wiluna Greenstone Belt, Eastern Goldfields Province, Yilgarn Block, Western Australia., Geological Society of Australia. ISBN 0-909869-55-3.
- Lesher, C.M., Arndt, N.T., and Groves, D.I., 1984, Genesis of komatiite-associated nickel sulphide deposits at Kambalda, Western Australia: A distal volcanic model, in Buchanan, D.L., and Jones, M.J. (Editors), Sulphide Deposits in Mafic and Ultramafic Rocks, Institution of Mining and Metallurgy, London, p. 70-80.
- Golightly, J.P. (1981): Nickeliferous Laterite Deposits. Economic Geology 75, 710-735.
- Schellmann, W. (1983): Geochemical principles of lateritic nickel ore formation. Proceedings of the 2. International Seminar on Lateritisation Processes, Sao Paulo, 119-135.
- Evans, A.M., 1993. *Ore Geology and Industrial Mineras: An Introduction* 3rd ed. Blackwell Publishing.
- Blatt, Harvey and Tracy, Robert J.; 1996, *Petrology: Igneous, Sedimentary, and Metamorphic*, 2nd ed., p. 359-360, W. H. Freeman, ISBN 0-7167-2438-3.
- Vernon, Ron H., 2004, *A Practical Guide to Rock Microstructure*, Oxford University Press, Oxford. ISBN 0-521-89133-7 .
- Blatt, Harvey and Robert J. Tracy, 1996, *Petrology: Igneous, Sedimentary and Metamorphic*, 2nd ed., pp. 359-365, Freeman, ISBN 0-7167-2438-3.



- Blatt, Harvey and Tracy, Robert J.; 1996, *Petrology: Igneous, Sedimentary, and Metamorphic*, 2nd ed., p. 463-466, W. H. Freeman, ISBN 0-7167-2438-3.
- R. V. Dietrich - Migmatites .
- North Cascades National Park: Orthogneisses and Migmatites.
- Cooma Complex, SE Australia .
- Blatt, Harvey and Robert Tracy, 1995, *Petrology: igneous, sedimentary, and metamorphic*, Freeman, ISBN 0-7167-2438-3 .
- Camacho, A., Hensen, B.J., Armstrong, R., *Isotopic test of a thermally driven intraplate orogenic model, Australia', Geology, 30, pp. 887-890* .
- The Petermann Orogeny, Central Australia .
- Rapp, Robert P., Shimizu Nobumichi, and Marc D. Norman. Growth of early continental crust by partial melting of eclogite. *Nature* 425, 605-609 (9 October 2003) .
- Blatt, Harvey and Robert J. Tracy (1996). Petrology; Igneous, Sedimentary, and Metamorphic, 2nd Ed., W. H. Freeman. ISBN 0-7167-2438-3.
- Gall, Daniel G. and Vincas P. Steponaitis, "Composition and Provenance of Greenstone Artifacts from Moundville," Southeastern Archaeology 20(2):99-117 [2001]).
- Steponaitis, Vincas P. Prehistoric Archaeology in the Southeastern United States, 1970-1985. Annual Review of Anthropology, Vol. 15. (1986), pp. 363-404.
- Luth, R. W., *Mantle volatiles -- distribution and consequences.* In *The Mantle and Core* (ed. R. W. Carlson) Volume 2 Treatise on Geochemistry (editors H. D. Holland and K. K. Turekian), Elsevier-Pergamon, Oxford, pages 319-361 (2003). ISBN 0-08-043751-6.
- Sandiford M., Hand M., Sandra McLaren, S., 2001. *Tectonic feedback, intraplate orogeny and the geochemical structure of the crust: a central Australian perspective.* In "Polyphase tectonism and reactivation mechanisms in metamorphic belts", Geological Society of London, Special Publication.
- Blatt, Harvey and Robert Tracy, 1995, *Petrology: igneous, sedimentary, and metamorphic*, Freeman, ISBN 0-7167-2438-3.
- Luth, R. W., *Mantle volatiles -- distribution and consequences.* In *The Mantle and Core* (ed. R. W. Carlson) Volume 2 Treatise on Geochemistry (editors H. D. Holland and K. K. Turekian), Elsevier-Pergamon, Oxford, pages 319-361 (2003). ISBN 0-08-043751-6.
- Blatt, Harvey and Robert J. Tracy, 1996. *Petrology*. 2nd ed, W.H.Freeman, p.355. ISBN 0-7167-2438-3.